Improve the Spatial resolution of distributed optical sensors by designing a new detection scheme

1Mohammadreza Soltani and 2Sayed Emadodin Sajjadi Jazi

1Department of Electrical Engineering, Tiran Branch, Islamic Azad University, Tiran, Iran.
2Department of Applied Science, Malekeashtar University, Malekeashtar, Iran.

ABSTRACT
Distributed optical sensors use one of the three optical Reflectometry methods to measure their desired feature. This paper surveys Optical Frequency Domain Reflectometry (OFDR) method. A major part of the distributed sensor is its detection part which significantly affects the system's performance. There are four popular detection schemes two of which have been combined and simulated in a new detection scheme. Finally the effects of this new structure are presented for the improvement of the spatial resolution and noise reduction in sensing system.

INTRODUCTION

Distributed optical sensors are based on one of the three Reflectometry methods: Optical Time Domain Reflectometry (OTDR), Optical Low Coherence Reflectometry (OLCR) and Optical Frequency Domain Reflectometry (OFDR). OTDR is often used in systems with long length and has low spatial resolution. OLCR has a good spatial resolution but is useful in systems with low length. The OFDR method can obtain simultaneously good resolution in long length systems. This property has led to a wider usage and priority of the OFDR than other two methods (Zheng, 2005).

One of the main parts of the distributed optical sensors is the detection part which converts light into electrical signals and plays an important role in the overall performance of the system (Zheng, 2004). This paper presents the analysis and simulation of a new detection method, which leads to spatial resolution improvement and noise reduction. Accordingly, the OFDR technique and detection methods are introduced, and then the designed Method is described and simulated.

2. Method:
2.1 OFDR method:

The method of OFDR can be explained according to figure 1.

Fig. 1: OFDR method
Firstly, the output beam of a tunable laser source will modulate with a sawtooth waveform (Frequency Modulated Continues Wave method). Thus, the laser frequency fluctuates around a central value, $\nu_0$, formulated as (1) (Yuksel, 2010)

$$\nu(t) = \nu_0 + \gamma t$$  \hspace{1cm} (1)

Where $\nu_0$ is the frequency at the center of the modulation period and $\gamma$ is the frequency modulation rate per second. Then the modulated light is divided into two beams by a coupler. The first beam enters to the reference arm and the second enters to the test arm. The light in the reference arm is reflected by a mirror at the end of the arm. In the test arm, it is reflected by connectors, bends, Environmental changes, etc. The optical path difference between two beams leads to a difference in the frequencies of the two reflected signals (Yuksel, 2010). When arrived at the coupler, signals recombine to produce a beat signal. The frequency of beat signal equals to the frequency difference of the two interfering beams (Yuksel, 2010),

$$f_b = \frac{f_m \Delta \nu x_i}{c}$$  \hspace{1cm} (2)

Where $f_m$ is the frequency of modulation, $\Delta \nu$ is the frequency change of the laser beam and $c$ is the velocity of light. The initial phase of the beat signal can be written as

$$\phi_{b0} = \frac{2\pi x_i}{\lambda_0}$$  \hspace{1cm} (3)

Where $\lambda_0$ is the central wavelength of the laser beam and $x_i$ is the distance of reflection cause and laser source which equals to (Yuksel, 2010)

$$x_i = 2V_g \tau$$  \hspace{1cm} (4)

Where $V_g$ is the group velocity and $\tau$ is the time difference between the reflected signal from the end of reference arm and the reflected signal from reflect position. The intensity of beat is signal (Zheng, 2004)

$$I(x_i, t) = I_0[1 + V \cos(2\pi f_m t + \phi_{b0})]$$  \hspace{1cm} (5)

Where $I_0$ is the average intensity of the two beams and $V$ is the visibility. The spatial resolution of OFDR equals to (Zhao & Guan, 2010)

$$\Delta z = \frac{c}{2n\Delta \nu}$$  \hspace{1cm} (6)

All systems which are based on OFDR technique (such as distributed sensors), extract required information from frequency, phase, intensity of the beat signal or a combination of these. In theory, (according to equation 6) it is seen that spatial resolution is related to the rate of tunable frequency of the laser source, but in practice the detector also affects significantly spatial resolution (Gifford, 2007).

**Detection:**

After interference and producing the beat signal, the reference and test signals enter the detector. There are four common detection methods: conventional, different polarization, balanced and quadr (Zheng, 2005). The main advantages of each of these methods are respectively: simplicity, independence of the polarization state of light, common mode noise reduction and high sensitivity (Zhao & Guan, 2010). The structures of conventional and quadr methods are shown in figure 2.
Fig. 2: Structures of conventional and quadr methods

The method presented here is the combination of balanced and quadr methods shown in figure 3.

Fig. 3: Schematic view of the designed detector

Simulation:

For simulation, an OFDR system is designed with structure shown in Figure 4. In order to achieve accurate and real results, commercial optical components are used.

Fig. 4: Designed OFDR system

The central wavelength of the laser is set on 1550nm, wavelengths sweep rate on 20 nm/s, frequency sweep rate on 2.5THz/s and wavelength interval change on 2nm (from 1549 to 1551). The laser source is TLB-6600-H-CL with 10 mW power. After the calculation and considering losses, the transmitted powers to the main and auxiliary interferometers are 7.5mW and 1 µW respectively. The laser beam transmitted into the main interferometer is divided into two parts of 99.5% and 0.5% by a tunable coupler (F-CPL-1550-N-FP model). The test arm is a 500 meter fiber (SMF-28) with a bending with 3dB loss located at a 100m distance and a connector with 0.3dB loss located at a 250m distance.

Reflected and back scattered signals from the test arm interfere by the reference arm signal through the 50/50 coupler and lead to the main beat signal formation. Beat frequencies of bending and connector, according to equation 2, are 2.5 and 6.25MHz respectively. These signals are transmitted to the detector and then amplified by the amplifier (HVA-15M-60-B) and subsequently entered to the DAQ card (NI-PCI-6115).
MATLAB software is used to analyze and simulated the proposed structure. The system with a conventional detector is compared to the system with the designed detector. The designed structure used for simulation is shown in Figure 5.

**Fig. 5:** Designed structure for simulation

The resulted diagram (magnitude versus frequency of beat signal) in case of using the conventional detector is shown in Figure 6. The first and last peaks correspond to the beginning and end of the fiber, the frequency peak of 6.25MHz is related to the connector, and the drop at 2.5MHz is related to the bending. The fluctuations are also due to the system noises (Gifford, 2007).

**Fig. 6:** Resulted diagram in case of using the conventional detector

Theoretically, according to equation 6, the spatial resolution must be 400 µm but if calculated from the chart peaks it decreases (increases in numerical value) to 22 mm (Yuksel, Wuilpart&Megret, 2007). The cause of this phenomenon is that the noises in the environment influence on the sensor.

The peak related to the connector in Figure 6 is shown in Figure 7. After the magnification, its 3dB bandwidth is 550 Hz, equal to 22 mm spatial resolution.
Fig. 7: The spatial resolution of OFDR system with conventional detector. In the following, the designed detector is examined. The resulted diagram is presented in Figure 8.

When the peak related to the connector is magnified, Figure 9 is achieved. Here it becomes clear that spatial resolution is improved to 9.2 mm which is a very desirable result (Geng, 2011).

It is also clear from Figure 8 that the fluctuations decline compared to the previous state (Figure 6). By using the simulation (according to Figure 10), the cause of this phenomenon is determined.
Because of the initial balance structure and secondary balance structure in this design, the shared optical noises and the secondary electrical noises eliminate respectively (Sang, 2008). These results are presented in Figure 11.

Fig. 10: Simulation structure for checking the ability of designed detector in noise reduction

Fig. 11: The ability of designed detector to noise reduction

Results:
This paper showed that by using the designed detector the spatial resolution of distributed optical sensor improves from 22mm to 9.2mm. This improvement in OFDR system can be used in cases that higher accuracy is needed and thus makes the sophisticated OLCR method unnecessary (Sang, 2008). It also showed that the optical and electrical system noises decreased which is a significant change on its own.

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REFERENCES


