Enhancement of Distributed Fiber Optic Vibration Sensors

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Abstract. The paper deals with the enhancement of sensor system utilizing the standard single mode optical fiber as a distributed sensor of the mechanical vibrations. Many up-to-date solutions are based on detection of backscattered signals from interrogating optical pulses sent down the sensing optical fiber. Previous solutions suffer from insufficient frequency of optical pulses that is limited by the length of sensing fiber and so is the sample frequency from single point along the fiber, which makes classification of an event less accurate and false alarms may arise. This article presents a technique of information enrichment based on frequency-time division principle.

Keywords: Distributed optical fiber sensor · Mechanical vibrations · Optical modulator · AOM · Pulse multiplier · Frequency shifter · ϕ-OTDR

1 Introduction

Optical fiber-based sensor applications have been an attractive research area for several past decades. Fiber construction, the principle of operation (total reflection) and the form of signal (light) allows not only to transmit data with very high speed and very low bit error rates but also to sense neighborhood because optical fiber parameters are partially influenced by effects such as temperature, strain, vibrations or strong ambient electromagnetic field and this has an impact on optical signal sent through the fiber. These facts can be used for sensing purposes, [1].

Many sensor applications are point sensors or quasi-distributed but more and more applications using optical fiber in fully distributed manner are investigated where not only physical quantity values are measured but also the location information is obtained. Fully distributed fiber optic sensors can be used to measure various physical quantities such as temperature, strain, mechanical vibrations along the whole fiber length. Application areas of these sensors are pipelines, rails, frontiers, territories, communication networks, etc., [1]. It was proven that long ranges of fiber length can be reached for measurement – from tens of meters up to hundreds of kilometers, [9].

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2 State of the Art

Distributed fiber sensors [2] belong to a very attractive group in the fiber optic sensor area as the fiber behaves like hundreds or thousands of sensors spread along it. Signals from that sensor can be used for detection, localization and classification of various events along the fiber such as walking people, running cars, trains, engineering works, and by other objects producing mechanical vibration that can be sensed by an optical fiber. To enable this, a fiber response to an interrogating signal has to provide not only information about the value of measured quantity and its changes but also the information about the position along the fiber where the processed signal was generated. Many solutions of this issue are based on backscattering principle, [5]. The basic architecture of such system is shown in Fig. 1.

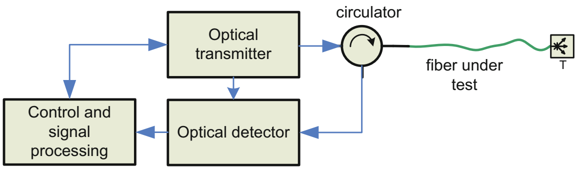

Fig. 1. Architecture of the sensor using backscattering and reflectometry principle

Distributed fiber sensors enable measurement of various quantities such as fiber loss pattern, temperature, pressure or vibrations at the scale from several meters up to hundreds kilometer range depending on particular solution. Spatial resolution that can be reached is of submeter order for short sensor lengths (up to several tens of meters) or in tens or hundreds meters for long range sensors (tens of kilometers or longer).

Localization of the measured physical quantity is most frequently based upon the time difference between the time instant of short-time and high power pulse transmission and the time instant of the fiber response sampling. The fiber response contains a portion of the light signal that was generated by scattering process. Portion of this scattered signal is re-captured by the fiber and propagates either back (in opposite direction than the original pulse was sent) or in the direction together with original signal or in both directions. The scattering process can be influenced by a physical quantity (temperature, pressure, radiation, strain, etc.), and the values and/or changes in a received signal can be detected and measured by signal processing module.

Backscattered signal can occur due to either elastic and/or inelastic effects. Elastic effects do not add new frequency components but inelastic ones cause new optical frequencies occurrence in the signal. The most known elastic effect is Rayleigh scattering, and Brillouin and Raman scatterings belong among inelastic ones. Rayleigh scattering effect was used in our experiments. There is a number of schemes based on Fig. 1, but φ-OTDR principle [3] with coherent detection is one of the most promising solutions. There has been a lot of research work done during more than two past decades, e.g. [4, 5, 7, 8].

The pulse width τ influences spatial resolution R that can be calculated as:

$$R = \frac{\tau v_g}{2}, \quad (1)$$

where v_g is the light group velocity in the fiber. The resolution can be increased by narrowing the interrogation pulses. On the other hand narrower pulse carries less energy and therefore shorter ranges of the sensing optical fiber can be reached because of the limited detector sensitivity and noise presence.

Figure 2 shows the sequence of pulses sent to the fiber and the fiber responses to them. It is clear that the pulse period T_P should be longer than the response T_r of the fiber to the pulse (see Fig. 2), otherwise the responses from the successive pulses would overlap and the information from the portion of the fiber will be lost:

$$T_{Pmin} = \frac{2L}{v_g}, \quad (2)$$

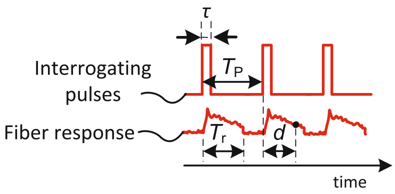

Fig. 2. Interrogating optical pulse sequence and the fiber response

where L is the sensing fiber length.

For example, if the length of standard single mode fiber is 10 km and wavelength 1550 nm is used, the pulse period should be at least 100 μs.

According to the time delay d between instance of light pulse transmission and the time instance of the response sample reception (see Figs. 2 and 3), the location x on the fiber of response generation can be calculated using formula

$$x \approx \frac{d * v_g}{2}. \quad (3)$$

Geographical location of the event can be derived by approximation between two closest points along the fiber that have precise geographical locations associated and stored in a database.

Typical waveform of the fiber response on narrowband interrogating pulses after conversion to electrical form is shown in Fig. 4. The course shows rapid signal attenuation and high fluctuations. The attenuation is caused by double attenuation both of interrogating pulses traveling in forward direction and of backscattered signal propagating in backward direction. Fluctuations of backscattered signal seen in the figure occur due to the usage of ultra-narrow laser source, random locations of

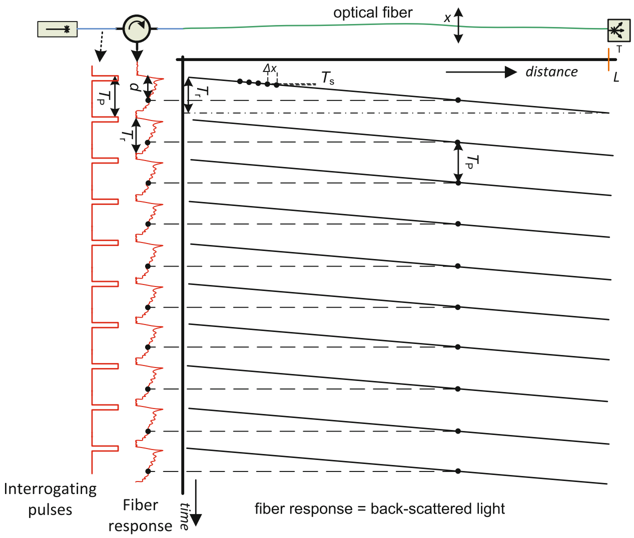

Fig. 3. Time-spatial response of the fiber to the sequence of optical pulses

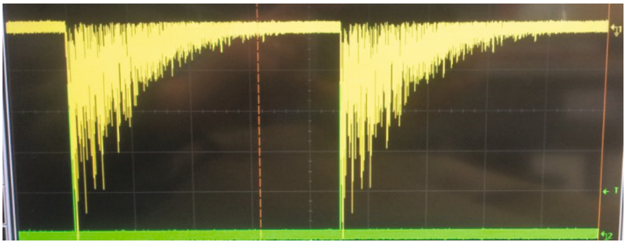

Fig. 4. Typical fiber response after o/e conversion (yellow trace at the top) to narrow interrogating pulses (green trace at the bottom)

scattering centers within the fiber and random phases of scattered signals that are superimposed during the propagation to the receiver side, [5].

3 Design of Novel Pulse Frequency Multiplier

As mentioned above the interrogating pulse frequency is restricted by the length of sensing fiber (see Eq. 2) to prevent from fiber response overlapping. This can result in lack of information for a detailed classification process of an event from the location of disturbance occurrence, mainly if the sensing fiber length is large, above 100 km (e.g. maximum number of samples from one location of fiber 100 km long is 1000 per second). The idea of overcoming this limit is to design a module that results in frequency separation of fiber responses to a pulse sequence, which allows the fiber responses to overlap in time and to send interrogating pulses more frequently. The basis of such module is a frequency shifter that includes frequency shifting circle for a pulse sequence that is periodically repeated. A scheme of such system is depicted in Fig. 5. To provide superior sensitivity ultra-narrow and stable laser is required (linewidth in the range of hundreds Hz). An optical pulse generator produces only one pulse per period T_P, while following pulse multiplier and frequency shifter adds other pulses that are mutually shifted both in frequency by Δf and in time by T_N.

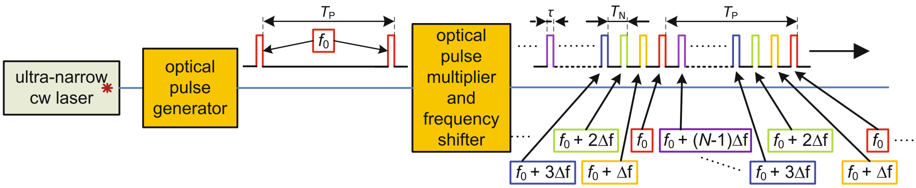

Fig. 5. Principle of pulse multiplication

The number of pulses N in one period T_P, and the periods T_P and T_N depend on the sensing fiber length and the number of samples per second we want to obtain from one location. For example, if we have a 100 km long fiber and we would like to have 25 000 samples per second from any location along the fiber, we need to send an interrogating pulse each 40 µs, while the minimum value of T_P is approximately 1 ms. Therefore, the pulse multiplier and frequency shifter has to generate at least additional

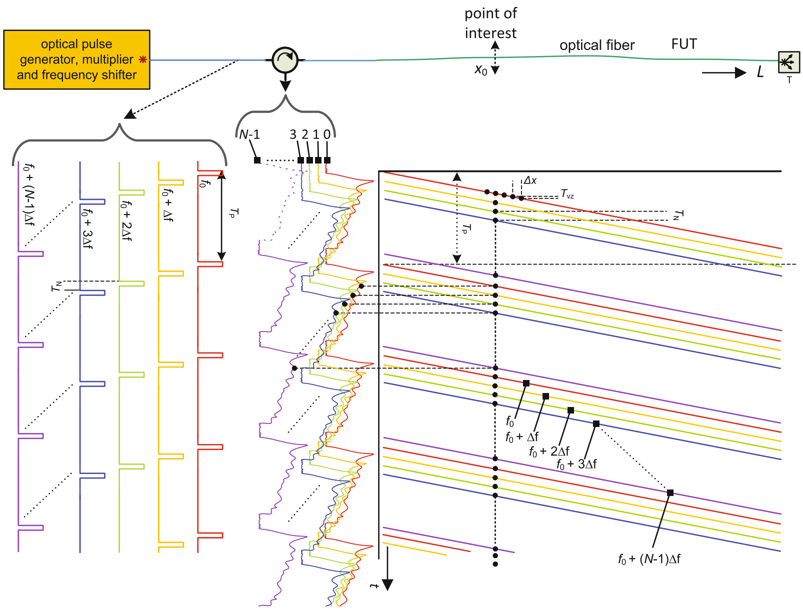

Fig. 6. Space-time projection of interrogating pulses and fiber responses

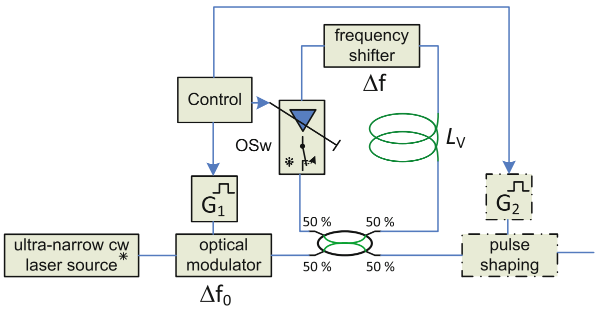

Fig. 7. Optical pulse multiplier scheme

24 pulses per period T_P with different carrier frequency (frequency shifted) from first pulse frequency f_0 to fulfil both requirements.

Figure 6 shows the system operation in time. It can be seen that high power interrogating pulses are neither overlapping in time nor in frequency, while fiber responses overlap in time but not in the frequency domain, so that the signal processing module can separate the responses and then rearrange the obtained data to get more detailed information from the location along the fiber. After response signal processing *N*-times more pieces of information can be obtained from one location along the fiber. The scheme of optical pulse multiplier is depicted in Fig. 7.

Laser source generates continuous beam that is modulated by optical modulator (we used AOM in practical realization) with frequency shift Δf_0 and the output pulse is equally divided both towards the optional pulse shaper and to the optical loop. The optical loop consists of an optical fiber segment of length L_V introducing delay required between consecutive pulses, frequency shifter introducing appropriate frequency shift Δf and optical switch and amplifier that compensates an attenuation of the delay fiber in the loop and attenuation caused by optical coupler and also breaks the loop in time instants when the first optical modulator generates original pulse sequence. An optional pulse shaper (e.g. EOM) can be used to set required pulse duration and shape.

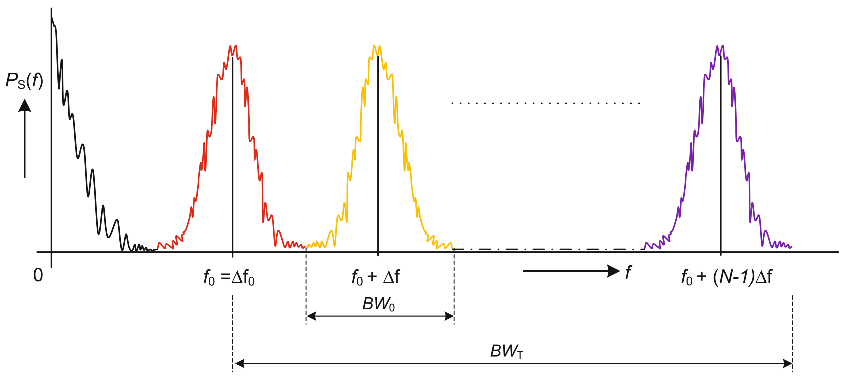

Fig. 8. Spectra of fiber responses to frequency shifted pulses

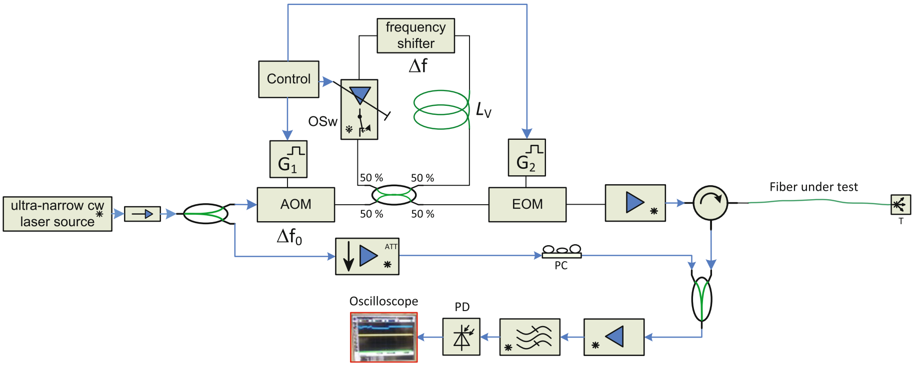

Fig. 9. Scheme design used for theory validation

Figure 8 shows the spectrum of received response after o/e conversion when coherent detection system is implemented.

Test bed of the φ-OTDR sensor system was designed and constructed according to the design from Fig. 9. It is standard φ-OTDR sensor architecture with coherent detection, except of adding the pulse multiplier from Figs. 7 and 10 shows records of various signals obtained by Infinium oscilloscope MSO9104A for the case when the number of pulses was doubled. The signal at the top of the screen (blue color) is control signal of the optical switch OSw. The signal below (yellow color) represents the fiber response after coherent reception and o/e conversion. The third signal from top (red color) represents control signal G1 of AOM that generates main pulses. The fourth

Fig. 10. Digital oscilloscope records of control electrical signals, fiber response after o/e conversion and its spectrum

signal corresponds to pulses outgoing from EOM after multiplication. Signal at the bottom shows the spectrum of converted fiber response. It can be seen that the spectrum contains two lobes corresponding to pulses with two frequency carriers where the distance between their peaks is 40 MHz.

It is clear that this solution brings some issues that add complexity to the plain φ-OTDR sensor system. In addition to the pulse multiplier and frequency shifter module described above an o/e converter with wider bandwidth is required and so is a data acquisition system. Signal processing unit with higher computing performance has to be also used.

4 Conclusion

New technique how to get more information from any location along the sensing optical fiber has been designed. Using frequency shifting, delaying and pulse multiplication more frequent interrogating pulse generation is allowed without interference among the responses to individual pulses. This technique helps to improve classification accuracy of the vibration sources along the long fibers and to decrease the number of false alarms generated by related monitoring system.

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