Optik 125 (2014) 441–445

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

150 km long distributed temperature sensor using phase modulated probe wave and optimization technique

Himansu Shekhar Pradhan, P.K. Sahu*

School of Electrical Sciences, Indian Institute of Technology Bhubaneswar, Bhubaneswar 751013, Odisha, India

ARTICLE INFO

Article history:
Received 21 February 2013
Accepted 30 June 2013

Keywords:
Brillouin optical time domain analysis
Differential Evolutional algorithm
Signal to noise ratio
Brillouin frequency shift
Avalanche photo diode

ABSTRACT

This paper describes and demonstrates the performance enhancement of a 150 km distributed sensing system based on Brillouin optical time-domain analysis (BOTDA). We present a BOTDA system combining the phase modulation and global evolutionary computing based optimization technique (Differential Evolution algorithm (DE)) for receiver optimization. We achieved an SNR improvement of 3.3 dBm compared to amplitude modulated probe wave for 150 km sensing range. We successfully demonstrate the presence of hot spot at a distance of 51 km of the sensing fibre for different temperatures.

1. Introduction

Optical fibre sensor based on Brillouin scattering has been widely studied over the last two decades because of its capability to measure both strain and temperature simultaneously. Basically, four different categories of Brillouin distributed sensors have been developed for real-time sensing of strain or temperature for Oil and Gas industries as well as for Civil engineering studies namely, (i) Brillouin Optical Time Domain Reflectometry (BOTDR) [1], (ii) Brillouin Optical Time Domain Analysis (BOTDA) [2], (iii) Brillouin Optical Frequency Domain Analysis (BOFDA) [3] and Brillouin Optical Correlation Domain Analysis (BOCDA) [4]. In BOTDR sensing system, only one end of the fibre is accessible and the other end of the fibre is cleaved. The temperature or strain profiles are extracted from the Brillouin power change due to temperature and strain variation. The disadvantage of BOTDR system is that the fibre nonlinearities play a major role in the degradation of the sensing accuracy. One of the major fibre nonlinearity is the stimulated Brillouin scattering which is generally caused by the input launched power when it exceeds the threshold power level [5]. Similarly, BOFDA and BOCDA sensing system offer good spatial resolution [3,6] but the downside is that it has slow data acquisition rate or the sensing speed, complicated design structure and limited to the overall sensing range. On the other hand, BOTDA has attracted for distributed sensing of temperature and/or strain for a long-haul sensing system. Recently, the BOTDA system is analyzed towards the milli-metre spatial resolution using dark pulse mechanism [7]. Therefore, the BOTDA sensing system is very much effective compared to all other sensing systems which are described earlier. The analysis of BOTDA system offers fast and real time measurement of temperature and/or strain by measuring Brillouin frequency shift (BFS) produced by temperature or strain variation in optical fibres [8]. The BOTDA system can be designed by using either one or two laser sources.

In this paper, we have proposed a BOTDA sensing system with phase modulated continuous probe wave using a single laser source. Thus, it is cost effective and eases to implement. Our system comprises a Brillouin loss based system because the launched continuous wave power is more than the pulse pump power due to the phase modulator used instead of the intensity modulator for probe signal power generation. As the Brillouin loss based BOTDA system is more effective than the Brillouin gain based system [9], thus, the advantage of our proposed system is that we have observed the performance improvement in terms of SNR and the sensing resolution. The proposed stimulated Brillouin scattering based sensor has the capability for measuring the absolute physical properties such as strain and temperature over a longer sensing range. The BOTDA sensor employs a pump pulse and a CW probe beam launched to a single mode optical fibre in the opposite direction and detects the amplified Brillouin back scattered signal, amplified by two light beams and acoustic wave mixing [10]. The sensing mechanism of this system is that If the frequency difference $\Delta\nu = \nu_p - \nu_{cw}$ between the pulse pump and continuous probe waves is tuned to around the Brillouin frequency shift ν_B [16] at a location along the test fibre then the probe signal is amplified at that point due to stimulated Brillouin scattering effect between the pump and probe

* Corresponding author. Tel.: +91 6742306245.
E-mail addresses: hsp10@iitbbs.ac.in (H.S. Pradhan), pks@iitbbs.ac.in (P.K. Sahu).

0030-4026/$ – see front matter © 2013 Elsevier GmbH. All rights reserved.
http://dx.doi.org/10.1016/j.ijleo.2013.06.078

lights. For this reason, it is possible to measure the distributed temperature and strain by measuring the time-dependent probe light power for various $\Delta\nu$ values, and by obtaining the Brillouin frequency distribution along the fibre length. Other reported work in the field of distributed sensor using BOTDA system mainly focused to increase the SNR, the sensing range and spatial resolution by using optical pulse coding [11], using Brillouin loss based system instead of gain based system [12] using dark pulse [13] etc. Recently, a Brillouin echo based distributed sensor using π phase pump pulses is demonstrated experimentally with high spatial resolution [14]. But the downside of the above echo based sensing system is that the cancellation of the second Brillouin echo which is detrimental for the measurement. However, several numerical alternatives are proposed to cancel the undesired effects of second Brillouin echo [15]. In this paper, we have investigated the use of phase modulated continuous probe wave and the receiver optimization using evolutionary computing technique for improving the SNR and sensing resolution of the proposed BOTDA system.

The optimization of the avalanche photo diode is done by maximization of the optimum gain using evolutionary computing algorithm (DE). We have compared the Brillouin gain spectrum of the proposed system with amplitude modulated probe wave based BOTDA system. We have simulated the proposed BOTDA system by taking different data rates and plotted the SNR vs. data rates and we have found SNR enhancement in both non optimized and optimized receiver compared to intensity modulated probe wave system. In particular, we have shown in the simulation results of phase modulated BOTDA system compared to the intensity modulated BOTDA system in terms of SNR enhancement and Brillouin gain spectrum.

2. Theory

2.1. Sensing principle of BOTDA sensor

The BOTDA sensor basically works on the principle of stimulated Brillouin scattering (SBS) effect. The stimulated Brillouin scattering is a fibre nonlinear effect created from the spontaneous Brillouin scattering. The SBS occurs when the launched input power to a single mode fibre is more than the Brillouin threshold power. The SBS is a parametric interaction between the incident light, the Stokes light, and an acoustic wave. The Brillouin frequency shift ν_B in an optical fibre is given in Eq. (1) [16].

$$\nu_B = \frac{2nV_A}{\lambda} \tag{1}$$

In the above expression, V_A is the acoustic velocity, n is the effective refractive index, and λ is the wavelength of the laser source. The Brillouin line width $\Delta\nu_B$ of the Brillouin gain spectrum is related to the phonon lifetime is given in Eq. (2) [17]:

$$\Delta\nu_B = (\pi\tau_B)^{-1} \tag{2}$$

where τ_B is the phonon lifetime.

The basic principle of the BOTDA sensing system is the pump pulse light is launched at one end of the sensing fibre and the continuous wave (CW) probe light is launched at the opposite end of the fibre so that it will propagate in the opposite direction. In this setup the pump pulse generates backward Brillouin gain in a single mode fibre. The centre frequency of Brillouin gain bandwidth is downshifted from the pump frequency ν to the Stokes frequency $\nu - \nu_B$ due to the pump and acoustic wave interaction. The CW light is amplified through the Brillouin interaction with the pump pulse when the frequency of the CW light will be in resonance with the Stokes frequency. The amplified CW light is detected by the photo detector at the input end of the fibre by time-resolved measurement. That means the power detected by the photo detector is time dependent. The CW light amplified and arrives at the input end of the fibre at time $t = 2L/\nu$ [17] after the launching of the pump pulse into the fibre. Where L is length of the fibre and ν is the velocity of the light. The CW light is amplified due to the Brillouin interaction of pump and probe wave. Therefore, the Brillouin gain factor (g) associated with the amplification is given in Eq. (3) [18]:

$$g = \frac{2\pi n^2 P_{12}^2 \gamma}{c\lambda^2 \rho V_A \Delta\nu_B} \tag{3}$$

where n is the refractive index of optical fibre, P_{12} is the photo elastic constant of the fibre, λ is the wavelength of the laser source, ρ is the density of the fibre, V_A is the acoustic velocity, $\Delta\nu_B$ is the Brillouin line-width, and γ is the coefficient of polarization.

The Brillouin frequency offset of an optical fibre dependant with the variation of temperature and strain in BOTDA system is given in Eqs. (4) and (5) respectively [19].

$$\nu_B(T) = \nu_B(T_0)[1 + C_T(T - T_0)] \tag{4}$$

$$\nu_B(\varepsilon) = \nu_B(0)(1 + C_\varepsilon \varepsilon) \tag{5}$$

In the above expression $\nu_B(T_0)$ is the Brillouin frequency shift at reference temperature, C_T is the temperature proportionality constant, T_0 is the reference temperature $\nu_B(0)$ is the Brillouin frequency shift of unstrained fibre and C_ε is the strain proportionality coefficient. The typical value of the frequency offset for a standard single mode fibre in room temperature is given in Eq. (6) [19].

$$\Delta\nu_B = C_{\nu\varepsilon}\Delta\varepsilon + C_{\nu T}\Delta T \tag{6}$$

where typically $C_{\nu\varepsilon} = 0.0483 + 0.0004(MHz/\mu\varepsilon)$ and $C_{\nu T} = 1.10 + 0.02(MHz/K)$.

2.2. Optimum gain of avalanche photo diode

In this paper we have used avalanche photo diode (APD) rather than the PIN photodiode for receiving the amplified probe light because the optical receivers employed an APD generally provide a higher SNR for the same input optical power. The improvement of the SNR is due to the internal gain of APD that increases the output photocurrent. We have investigated the APD in presence of thermal and shot noise. The APD receivers are not affected by the thermal noise because it generates from the electrical components that are not the part of APD. As in APD the internal gain is generated by the secondary electron–hole pairs through the process of impact ionization at random times, therefore, an additional contribution is added to the shot noise associated with the generation of primary electron–hole pairs. In effect, the shot noise currents of electron and hole will be treated as random and the variance of the total shot noise is expressed as Eq. (7) [20].

$$\sigma_s^2 = 2qM^2F_A(RP_{in} + I_d)\Delta f \tag{7}$$

In the above equation σ_s^2 is the shot noise variance, q is the charge of the electron, M is the internal gain of APD, F_A is the excess noise factor, R is the Responsivity of APD, P_{in} is the input optical power, I_d is the dark current and Δf is the effective noise bandwidth.

The excess noise factor can be expressed as in Eq. (8) [20].

$$F_A(M) = k_A M + (1 - k_A)\left(2 - \left(\frac{1}{M}\right)\right) \tag{8}$$

where k_A is the dimension less parameter and treated as ionization ratio of APD.

The expression of SNR by considering optical receiver as APD and the noises associated, i.e., thermal and shot is given in Eq. (9) [20].

$$\mathrm{SNR} = \frac{(MRP_{in})^2}{2qM^2F_A(RP_{in} + I_d)\Delta f + \sigma_T^2} \tag{9}$$