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Brillouin distributed temperature sensor employing phase modulation and optimization techniques

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ABSTRACT

The process of signal-to-noise ratio (SNR) improvement and the suppression of stimulated Brillouin scattering (SBS) effects on a long-range distributed sensor are presented in this paper. We have proposed an improved performance Brillouin distributed temperature sensor using phase modulation and optimization techniques. Global evolutionary computing-based optimization techniques (genetic algorithm (GA), particle swarm optimization (PSO) and differential evolution algorithm (DE)) are applied for both fiber and receiver optimization. The combination of phase modulation and the global evolutionary computing technique improved the SBS threshold power of the proposed system to an extent of 5.95 dBm. However, with receiver and fiber optimization, for an input power of 0 dBm, the proposed system provides SNR improvement up to 3.5 dB, for temperature sensing over a distance of 50 km with temperature resolution of 1.44 K and spatial resolution of 32 m without using filter. However, for the equivalent sensing range, we have achieved a temperature resolution as 0.51 K using the above optimized system with filter.

1. Introduction

Brillouin distributed fiber optic sensor has become more popular due to its unique advantage of accurately measuring both the temperature and strain simultaneously. The distributed fiber sensors are attractive because in this arrangement a single fiber optic cable can potentially replace thousands of individual point sensors. Besides this advantage, the sensor installation and maintenance issue is simplified using distributed sensor. Fiber sensors offer several advantages in terms of electromagnetic interference (EMI), light weight, ease of integration with structure, etc. A number of optical fiber properties have been studied under this work in order to determine how to optimize their Brillouin characteristics as well as the signal-to-noise ratio (SNR). Though the Brillouin scattering based technique can be used for sensing both distributed temperature and strain, but not simultaneously as a result of cross sensing. Parker et al. [1] studied the different possible ways to simultaneously detect temperature and strain using the Brillouin scattering but it is not standardized. It was in 1990s, that the Brillouin scattering-based approach was developed. The time domain representation of the scattering effect can be observed by Brillouin optical time domain reflectometer (BOTDR) [2] and Brillouin optical time domain analysis (BOTDA) [3]. The scattering effect can be observed in the frequency domain by Brillouin optical-fiber frequency domain analysis (BOFDA) [4]. Similarly, another technique for measurement of temperature using Brillouin scattering is Brillouin optical correlation domain analysis (BOCDA) [5]. BOFDA and BOCDA sensing system offer good spatial resolution [4,6] 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 for long-haul sensing system. In Brillouin sensor, basically two types of scattering mechanism are used, namely spontaneous scattering and stimulated scattering. In 2000, Kee et al. [7] used a spontaneous Brillouin distributed temperature sensing (DTS) system for the temperature measurement. Their approach aims to use a short-pulse width laser source at 1550 nm, with an accuracy of up to 35-cm spatial resolution over a sensing range of 1 km with a temperature resolution of 4.3 °C. Wait and Hartog [8] reported a Brillouin optical time domain reflectometer-based distributed sensor for temperature measurement with a 2 m spatial resolution over a 25 km of sensing range. In order to separate the Brillouin signal for Rayleigh backscattered signal a fiber Bragg grating notch filter was used. A 1550 nm distributed feedback laser source and erbium doped fiber amplifier were used to generate 200 mW power for the system. Soto et al. [9] applied optical pulse coding 127 bits simplex code to a spontaneous Brillouin distributed temperature sensor system. The reported performance improvement in terms of SNR of the sensing system was 7 dB at the receiver. In this approach using 10 mW power at the

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input end of the fiber, the observed temperature resolution and spatial resolution are 5 K and 40 m, respectively, over 30 km of sensing range. Bao et al. [10] demonstrate an automated distributed sensor system based on Brillouin scattering for temperature and strain measurement. This system offers centimeter scale spatial resolution for simultaneous temperature and strain sensing with strain accuracy of 10–30 $\mu\varepsilon$ and temperature accuracy of 1–2 °C. The system utilizes two types of fiber, namely polarization maintained fibers (PMF) and photonic crystal fibers (PCF) for temperature as well as strain measurement. This sensor was used to detect 1.5 cm crack in optical ground wire. Cui et al. [11] used Rayleigh backscattering effect of a microwave pulsed based probe wave to suppress the fluctuations due to the polarization in order to improve the signal intensity. In the experiment a single source of laser and a sensing fiber of 300 m with one end excess were used. This method of distributed temperature sensing claims the temperature accuracy of 1 °C and spatial resolution of 3 m. Brown et al. [12] demonstrated a dark pulse based Brillouin distributed fiber sensor. The experimentally obtained Brillouin spectra demonstrate that not only the dark-pulse configuration is capable for measurement of strain and temperature like the conventional pulse-based systems but also it gives much higher spatial resolution. For a 100 m sensing fiber a spatial resolution of 50 mm was reported with a strain measurement accuracy of 6 $\mu\varepsilon$.

Brown et al. [13] in 2007 presented a BOTDA system based on dark-pulse scattering that provides improved resolution, accuracy, and acquisition time over conventional BOTDA systems. Theoretically and experimentally they have validated the results. They have demonstrated the system with 20-mm resolution for strain measurement with an accuracy of $\pm 20\,\mu\varepsilon$ for 1 km of sensing range. Angulo-Vinuesa et al. [14] proposed a Raman assisted Brillouin optical time-domain analysis system. In this paper, both pump and probe signals were introduced in the sensing fiber in opposite directions with the Raman pumps. The splitting of the output of a Raman fiber laser employing proper wave length division multiplexers, results in Raman pumps. This system achieved a 2 m spatial resolution and 1.2 °C temperature resolution over a sensing range of 100 km. Recently, a Brillouin echo based distributed sensor with high spatial resolution using π phase pump pulses is reported [15]. However, the cancelation of the second Brillouin echo is a major issue in this design. Several numerical alternatives are proposed to cancel the undesired effects of second Brillouin echo [16].

In this paper, the objective is to design an improved performance Brillouin distributed temperature sensor system (BDTS) using spontaneous Brillouin scattering and phase modulation. A number of optical fiber properties are studied in this paper to optimize the parameters associated with the Brillouin characteristics such as Brillouin peaks, temperature resolution, spatial resolution and SNR. Beside these studies one of the major fiber nonlinear effect, i.e. the stimulated Brillouin scattering [17] has been analyzed in this paper. In order to increase the power delivered into fiber many SBS suppression techniques were reported in the literature [18–21]. These techniques improve the SBS threshold by modifying either the Brillouin bandwidth or by limiting the gain experienced by back reflection signals. One of the active SBS suppression method as reported in the literature describes the phase modulation of the incident light. Due to the phase modulation the effective SBS gain is decreased by changing the phase of the incident wave E-field, thus increasing the effective pump wave spectral width. In this case, with the help of controlling electrical waveform preferably sinusoids, combinations of multiple sinusoids, and pseudorandom bit sequences, the laser is dithered in either phase or in frequency. In our work, we proposed a method to mitigate the SBS effect using optimization techniques.

The SBS effect limits the launched input power to the fiber under test. However, the launched input power is critical [22] in attaining a desired SNR and is limited by SBS threshold power. In order to improve the SNR of the proposed system we have optimized the parameters associated with the SBS threshold power. The other reported work to increase the SBS threshold power is using PSO [23]. We have implemented the evolutionary computing techniques to maximize the SBS threshold power. We have implemented three different evolutionary computing techniques such as GA, PSO and DE for optimization. The major advantage of evolutionary computing method in contrast to conventional statistical method is that it will give the global solutions. Basically, in global search algorithms one needs to repeat the process many times to get the global solution. In connection with number of iterations we have shown that the results obtained using differential evolution algorithm (DE) is faster one to converge toward the global solution. Similarly, we have detected the Brillouin power by using heterodyne detection system [24]. Another focus we have given in this paper is to further improve the SNR for long sensing range applications by employing receiver parameters optimization. Previous reported works to improve the SNR are using distributed Raman amplification [25] or using optical pulse coding technique [26]. However, we have investigated the use of phase modulation, fiber optimization, the avalanche photo diode receiver optimization and use of digital filter for sensing range and SNR improvement of a BOTDR based sensor. We have achieved a greater sensing range and SNR improvement without using Raman amplification or coding techniques. We have considered the temperature sensing accuracy or temperature sensitivity as 0.33%/K [2] for calculating the temperature resolution of the sensing system. In particular, we have reported theoretical and simulation results showing a significant improvement of signal to noise ratio and the suppression of stimulated Brillouin scattering (SBS) effect using optimization techniques for 50 km of sensing range. We have calculated the temperature resolution of the sensing system using the Landau–Placzek ratio (LPR) [27] and windowing technique. The abbreviations and notations used in this paper are listed in Table 1.

2. Theoretical model and numerical simulation

In this paper, we have optimized the sensing media (optical fiber) as well as the receiver (avalanche photo diode) using global evolutionary computing techniques such as GA, PSO and DE. In fiber optimization process we have maximized the SBS threshold power as given in Eq. (1) [2].

$$P_{\mathrm{th}} = 21\frac{kA_{\mathrm{eff}}}{g_{\mathrm{B}}L_{\mathrm{eff}}} \tag{1}$$

where L_{eff} is the effective fiber length and given by Eq. (2).

$$L_{\mathrm{eff}} = \frac{1-e^{-\alpha L}}{\alpha} \tag{2}$$

Similarly, for the receiver optimization process we have calculated the optimum gain of the avalanche photo diode (APD). The approximate expression for the optimum gain is given in Eq. (3) [28].

$$G_{\mathrm{opt}} = \left[\frac{4k_{\mathrm{B}}TF_{\mathrm{n}}}{k_{\mathrm{A}}qR_{\mathrm{L}}(RP_{\mathrm{in}}+I_{\mathrm{d}})}\right]^{1/3} \tag{3}$$

In case of fiber optimization for SBS threshold power we have selected the three main parameters: effective area of the fiber core (A_{eff}), fiber attenuation coefficient (α) and Brillouin gain constant