SNR Enhancement of Brillouin Distributed Strain Sensor Using Optimized Receiver

Himansu Shekhar Pradhan and P.K. Sahu

Abstract This paper presents an improvement on signal to noise ratio (SNR) of long range Brillouin distributed strain sensor (BDSS). Differential evolution (DE) algorithm is used for receiver (avalanche photo diode (APD)) optimization. We have extracted the strain information of the proposed sensor using Fourier deconvolution algorithm and Landau Placzek ratio (LPR). SNR of the proposed system is realized using Indium Gallium Arsenide (InGaAs) APD detector over 50 km sensing range. We have achieved about 30 dB improvement of SNR using optimized receiver compared to non-optimized receiver at 25 km of sensing distance for a launched power of 10 mW. The strain resolution is observed as $1670\mu\varepsilon$ at a sensing distance of 50 km. Simulation results show that the proposed strain sensor is a potential candidate for accurate measurement of strain in sharp strain variation environment.

Keywords SNR · DE · APD · BDSS

1 Introduction

Nowadays, Brillouin distributed sensors become increasingly popular because of its ability to sense both temperature as well as strain. The distributed fibre sensors are more attractive toward the sensing applications due to their many advantages such as: distributed sensing replaces complex integration of thousands of electric sensor with one optical fibre system. These sensors offer the ability of being able to

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measure physical and chemical parameters along their whole length of the fibre on a continuously manner. The optical fibre is used as sensing element because it is cheap, light weight, flexible and immune to electromagnetic interference (EMI) [1, 2]. The distributed sensing system can be a cost-effective as well as flexible solution because of the use of normal telecommunication fibre as sensing element. A temperature measurement system using the signature analysis of Raman anti-Stokes and Stokes backscattered signal is demonstrated by Dakin et al. [3]. Raman scattering based temperature sensor are very popular because Raman signal separation is easier and conventional silica-based optical fibres can be used as the sensing element. Another advantage is that the temperature sensitivity of Raman sensor is about 0.8 %/K [4]. However, the downside is that the anti-Stokes Raman backscattered signal is extremely weak and about 30 dB weaker than the Rayleigh backscattered signal as a result a high sensitive receiver is required to receive weak backscattered signal. In order to mitigate the above mentioned difficulties, Brillouin scattering based distributed sensor is developed. The frequency shift of the Stokes Brillouin backscattered signal with strain was reported by Horiguchi et al. [5] in 1989. After their reported work, lots of research works on Brillouin distributed sensor are carried out by the researchers and industries. The mostly focused areas of research on Brillouin distributed sensor (BDS) is that the performance improvement such as: sensing range, sensing resolution, spatial resolution and SNR etc. SNR enhancement of BDS using different optical pulses coding such as simplex code [6], bipolar Golay codes [7], colour simplex coding [8] are reported in the literature. In this paper, we have proposed a BDSS system and extracted the strain profile using optical time domain reflectometer (OTDR) technique and LPR. In the proposed BDSS system, we have injected a short pulse to the sensing fibre and a spontaneous Brillouin backscattered signal is detected at the input fibre end. The received Brillouin backscattered signal intensity can be expressed as the convolution of the input pulse profile and the strain distribution along the fibre. We have calculated the SNR of the detecting signal using non-optimized and optimized parameter values of APD. We have included both thermal as well as shot noise of APD for calculation of SNR. In particular, we have shown the improvement of SNR of the proposed system using receiver optimization.

2 Theory and Simulation Model

The schematic of proposed SBSS system for 50 km sensing range is shown in Fig. 1. We have measured Brillouin backscattered signal using OTDR technique of the proposed sensor. The principle of OTDR technique is that an optical pulse is launched into fibre and the backscattered signal is detected at the input fibre end. The location information can be found out by the delay time and the light velocity in the fibre.

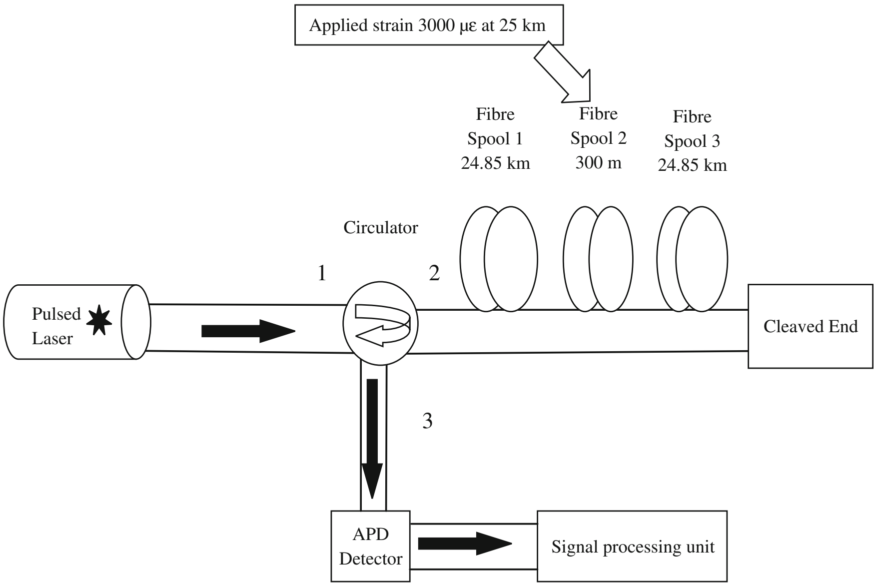

Fig. 1 The schematic of the proposed BDSS system

We have optimized the parameters of APD such as Responsivity R, dark current I_d and ionisation ratio k_A using DE algorithm. The optimum gain of the APD used as cost function for the optimization process and is given by [9]

$$G_{\text{opt}} = \left[\frac{4k_B T F_n}{k_A q R_L (R P_{in} + I_d)}\right]^{1/3} \tag{1}$$

In the above expression, k_B is the Boltzmann constant, T is the absolute temperature equal to 300 K, F_n is the excess noise factor, k_A is the ionization ratio or coefficient, q is the charge of an electron, R_L is the load impedance, R is the Responsivity, P_{in} is the input power to the receiver. The typical value of the other parameters of Eq. 1 are taken as $R_L = 1\,\text{k}\Omega$ and $F_n = 2$ [9]. We have used DE algorithm to maximize the cost function. In DE algorithm, we have used the mutation factor 0.5, number of populations 10 and number of generations 100 in our proposed algorithm. The maximization of APD optimum gain in Eq. 1 is done by taking three variables as R (from 1 to 9 A/W) I_d (from 1 to 10 nA) and k_A (from 0.01 to 1). We have considered the processes involved in DE algorithm [10] to maximize the optimum gain of APD. In the proposed system, we have considered the backscatter impulse response $f(t)$ defined as the backscattered signal power in response to an injected unit delta function signal. Assuming constant propagation loss of fibre throughout its length, $f(t)$ can be expressed as

$$f(t) = \frac{1}{2}\alpha_B v_g S p_{in} \exp(-2\alpha z) \quad (2)$$

where v_g is the group velocity within the fibre, S is the backward capture coefficient, p_{in} is the optical power injected to the fibre, α_B is the Brillouin scattering coefficient of the fibre defined as $\alpha_B = (8\pi^3 n^8 p^2 k_B T)/(3\lambda_0^4 \rho v_a^2)$ [11]. Where n is the refractive index of fibre core, p is the photoelastic coefficient, ρ is the density of the silica, v_a is the acoustic velocity and λ_0 is the wavelength of the incident light. In the proposed strain sensing system, the received backscattered power at the input of the fibre $P(t)$ can be expressed as the convolution of the injected pulsed power $p(t)$ and the backscatter impulse response $f(t)$ and is given by

$$P(t) = p(t) \otimes f(t) \quad (3)$$

In simulation, we have considered a pulse of width w_0, and power p_{in} is launched into the 50 km long fibre and have received the backscattered power at the input fibre end with the addition of white Gaussian noise. Similarly, for calculation of LPR, which is the ratio of Rayleigh signal intensity to Brillouin signal intensity, we have calculated the Rayleigh backscattered power. Rayleigh backscattered power P_R, with the function of fibre length z is given by [12]

$$P_R(z) = \frac{1}{2} p_{in} \gamma_R w_0 S v_g \exp(-2\gamma_R z) \quad (4)$$

where γ_R is the Rayleigh scattering coefficient. We have considered the strain dependence of the Brillouin backscattered signal intensity is given by $I_B = (I_R T)/(T_f(\rho v_a^2 \beta_T - 1))$ [13]. Where I_R and I_B are the Rayleigh and Brillouin backscattered signal intensities respectively, T_f is the fictive temperature, β_T is the isothermal compressibility and v_a can be expressed as $v_a = \sqrt{((E(1-\sigma))/(\rho(1+\sigma)(1-2\sigma)))}$ [13]. Where E is the Young's modulus and σ is the Poisson's ratio. The variation of Young's modulus of silica with the strain is given by $E = E_0(1 + 5.75\varepsilon)$ [14]. Where E_0 is the Young's modulus in unstrained fibre and ε is the tensile strain applied to the fibre. Assuming the Poisson's ratio is independent of strain, I_B can be rewritten as

$$I_B = \frac{k_1 I_R}{(k_2(1 + 5.75\varepsilon)) - 1} \quad (5)$$

where $k_1 = T/T_f$ and $k_2 = (E_0\beta_T(1-\sigma))/(((1+\sigma)(1-2\sigma)))$. To obtain the strain profile along the sensing fibre, we have considered the LPR at the unknown strain ε is compared with the known reference strain ε_R, and given by

$$\varepsilon = \frac{1}{K_s}\left(1 - \frac{\mathrm{LPR}(\varepsilon)}{\mathrm{LPR}(\varepsilon_R)}\right) + \varepsilon_R \tag{6}$$

The strain sensitivity of the proposed sensor is K_s. For calculation of SNR, we have used (InGaAs) APD receiver. The photo current of the receiver can be expressed as [9]

$$I_P = MRP_{in} \tag{7}$$

where R is the responsivity of the photo receiver and P_{in} is the input power to photo receiver. We have considered the noise powers such as: Gaussian noise, (σ_G^2) as well as thermal noise, (σ_T^2) and shot noise, (σ_S^2) of APD for calculation of total power. The shot noise power of APD can be calculated by the given expression $\sigma_S^2 = 2qM^2F_A(RP_{in} + I_d)\Delta f$ [15]. In the above expression, Δf is the effective noise bandwidth and F_A is the excess noise factor can be expressed as $F_A = k_AM + (1 - k_A)(2 - (1/M))$. Similarly, the thermal noise power of APD can be calculated by the given expression $\sigma_T^2 = 4(kT/R_l)F_n\,\Delta f$ [16]. Where F_n is the amplifier noise figure. The SNR of the proposed sensing system over a 50 km sensing range can be expressed as:

$$SNR = \frac{I_P^2}{\sigma_G^2 + \sigma_S^2 + \sigma_T^2} = \frac{M^2R^2P_{in}^2}{\sigma_G^2 + \sigma_S^2 + \sigma_T^2} \tag{8}$$

where I_P^2 is the Brillouin backscattered signal power at the output of APD and $\sigma_G^2 + \sigma_S^2 + \sigma_T^2$ is the total noise power of the proposed system. We have realized SNR of the proposed sensor using non-optimized as well as optimized receiver.

3 Simulations and Results

The optimum gain of APD is maximized using DE algorithm and the best solution shown in Fig. 2. We have calculated the Raleigh backscattered power and Brillouin backscattered power with additive white Gaussian noise of variance of $\sigma_G^2 = 10^{-7}\,\mathrm{W}$ for 50 km sensing range. A laser source operating at 1550 nm with 10 MHz linewidth is used for simulation. A rectangular pulse of width 100 ns and power 10 mW is launched to the sensing fibre and the backscattered signal is received at the input fibre end. The other parameters based on silica fiber such as $\alpha = 0.2\,\mathrm{dB/km}$, $k = 1.38 \times 10^{-23}\,\mathrm{J/K}, S = 1.7 \times 10^{-3}, n = 1.45, \gamma_R = 4.6 \times 10^{-5}\,1/\mathrm{m}, p = 0.286$, $\rho = 2330\,\mathrm{kg/m^3}$, $T_f = 1950\,\mathrm{K}$, $E_0 = 71.7\,\mathrm{GPa}$, $\beta_T = 7 \times 10^{-11}\,\mathrm{m^2/N}$ and $\sigma = 0.16$ are used for simulation. We have simulated the proposed 50 km strain sensor using Eq. 3. In the simulation process, we modeled a strained source with an artificial rectangular pulse variation of strain distribution around the point z = 25 km from

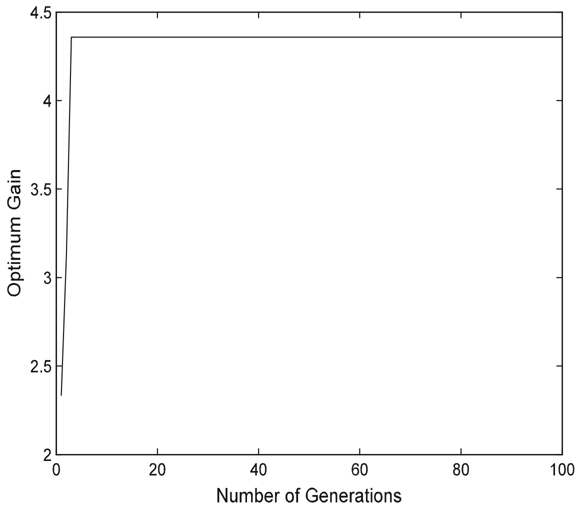

Fig. 2 The best solution of DE algorithm

the end point of the optical fibre whereas the rest of the fibre maintained at zero strain. We have calculated $LPR(\varepsilon_R)$ for unstrained fibre by taking $\varepsilon_R = 0\mu\varepsilon$. Similarly, $LPR(\varepsilon)$ for strained fibre is calculated by taking $\varepsilon = 3000\mu\varepsilon$. We have extracted the strain of proposed sensing system using FourD algorithm. The strain sensitivity K_s is $9.1 \times 10^{-4}\ \%\mu\varepsilon^{-1}$ [17] with respect to Brillouin intensity is considered for simulation process. The strain profile of the proposed system extracted using Eq. 6 and shown in Fig. 3. We have estimated the strain resolution by the exponential fit of the standard deviation of measured strain distribution versus distance. The strain resolution using FourD algorithm is shown in Fig. 4. We have observed the strain resolution of $1670\mu\varepsilon$ at 50 km distance using FourD algorithm. We have calculated SNR of the proposed

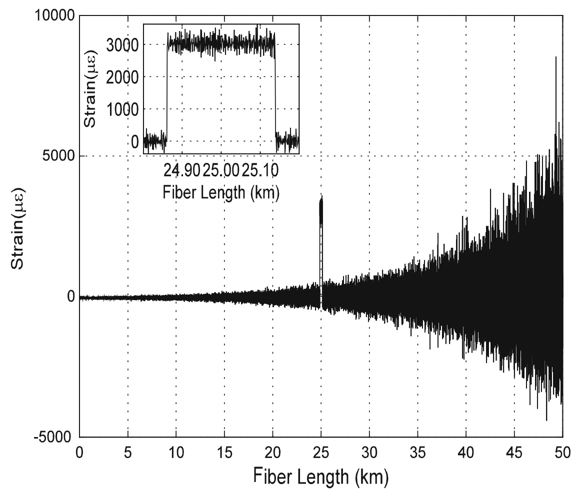

Fig. 3 Strain profile of the proposed system using FourD algorithm

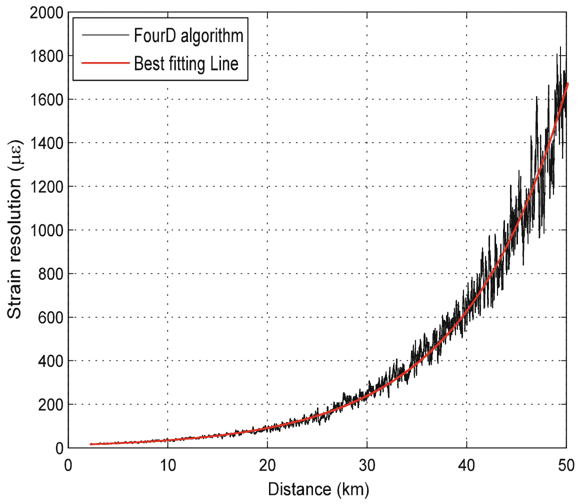

Fig. 4 Strain resolution of proposed system using FourD algorithm

system using InGaAs APD using non-optimized and optimized optimum gain for 50 km sensing range. The non-optimized parameter values 1, 0.9, 10 nA are used for R, k_A and I_d respectively in simulation process. The SNR of the proposed system is calculated using Eq. 8. Figure 5 shows the SNR of the proposed sensor using both non-optimized receiver and optimized receiver. The 30 dB improvement of the SNR is observed in Fig. 5 at 25 km of distance for optimized receiver compared to non-optimized receiver.

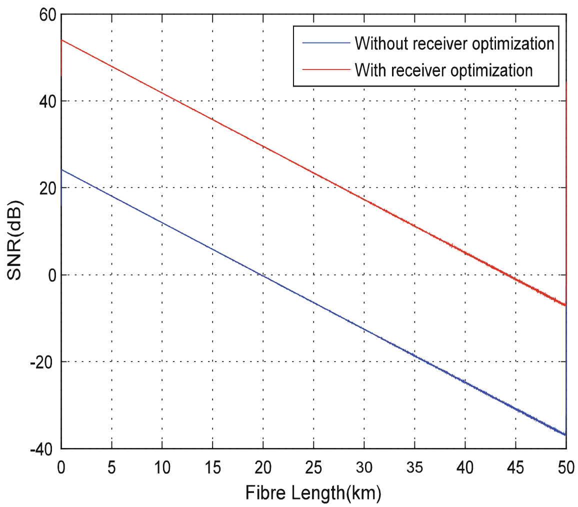

Fig. 5 SNR with and without receiver optimization of the proposed sensor

4 Conclusion

The improvement of SNR in Brillouin distributed strain sensor is investigated in this paper. The strain profile of the proposed system is extracted using LPR and FourD algorithm over 50 km sensing range. The optimization of receiver APD is done using DE algorithm. Using optimized receiver 30 dB improvement of SNR is observed at 25 km of distance. In the proposed strain sensing system, the strain resolution is observed $1670\mu\varepsilon$ at a distance of 50 km. Simulation results indicate that the proposed strain sensor can be used for accurate strain measurement in long range sensing applications.

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