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# Brillouin scattering spectrum character extraction based on genetic algorithm and seeker optimization algorithm①

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**Abstract**

A new hybrid optimization method based on genetic algorithm (GA) and seeker optimization algorithm (SOA) is presented in this paper. The hybrid algorithm optimizes SOA by using crossover and mutation operations in GA in order to improve the global search ability of SOA. Four algorithms, i. e. particle swarm optimization (PSO), SOA, GA and quantum-behaved particle swarm optimization (GA-QPSO) and GA-SOA are used to process the simulation and experimental data of Brillouin scattering spectrum (BSS) at different temperatures. The results show that GA-SOA improves the accuracy of extracting the center frequency shift and the minimum center frequency of Brillouin scattering spectrum compared with other three algorithms. The shift error is 0.203 MHz. Therefore, GA-SOA can be applied to the accurate extraction of BSS characteristics.

**Key words**: Brillouin scattering spectrum (BSS), seeker optimization algorithm (SOA), genetic algorithm (GA), particle swarm optimization (PSO), Brillouin frequency shift (BFS)

## 0 Introduction

With the rapid development of science and technology, sensing technology can be applied to various applications with the advantages such as absolute measurement, versatility of geometries, corrosion resistance, electromagnetic immunity and so on[1-3]. Distributed optical fiber sensors based on Brillouin scattering are favored by researchers at home and abroad.

By measuring the central frequency shift of the Brillouin scattering spectrum (BSS), the sensor system can achieve real-time monitoring of physical quantities such as temperature and strain. Because of the linear relationship between relative change of Brillouin frequency shift (BFS) and temperature and strain, how to obtain the BFS with high accuracy is the key of the sensing technology[4]. Particle swarm optimization (PSO) algorithm with adaptive parameters[5], improved Newton algorithm and Levenberg-Marquardt algorithm based on the finite element analysis algorithm have been used for feature extraction of BSS[6]. Although the above algorithms can complete the feature extraction, there are still some shortcomings such as low precision, strong dependence on initial value and so on. In order to further optimize the extraction accuracy of Pseudo-Voigt type BSS, the GA-SOA combining genetic algorithm (GA) with seeker optimization algorithm (SOA) is presented in this paper.

## 1 Fitting principle of BSS

Under ideal conditions, BSS is a Lorentzian spectral line[7]. However, during optical transmission in the actual fiber sensing system, there will be spectral broadening phenomenon such as natural broadening, Doppler broadening[8], broadening caused by insufficient phonon excitation, broadening caused by extinction ratio of pulse modulator[9], and so on. Thus, BSS is approaching the Gauss spectral line from Lorentzian spectral line, so that the actual BSS is between Lorentzian spectral line and Gaussian spectral line[10]. Therefore, by combing the Lorentzian spectra and Gaussian spectra according to the linear weights, the Pseudo-Voigt type spectrum is obtained as the fitting function of BSS[11]:

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$$f_B(x) = k\frac{(\Delta v_{B1}/2)^2}{(x - v_B)^2 + (\Delta v_{B1}/2)^2} + (1 - k)\exp\left[-2.773\left(\frac{x - \Delta v_B}{\Delta v_{B2}}\right)^2\right] \quad (1)$$

where $x$ is the Brillouin frequency, $k$ is the linear weight coefficient, $v_B$ is the BFS, $\Delta v_{B1}$ is Lorentz spectral linewidth and $\Delta v_{B2}$ is Gaussian spectral linewidth.

As shown in Fig. 1, the frequency sweeping method is a common measurement method for BSS detection. In a certain frequency range, according to certain frequency interval, the optical power along the optical fiber in each position corresponding to various frequency points of BSS is obtained. Then the location corresponding to BSS can be obtained by power curve fitting.

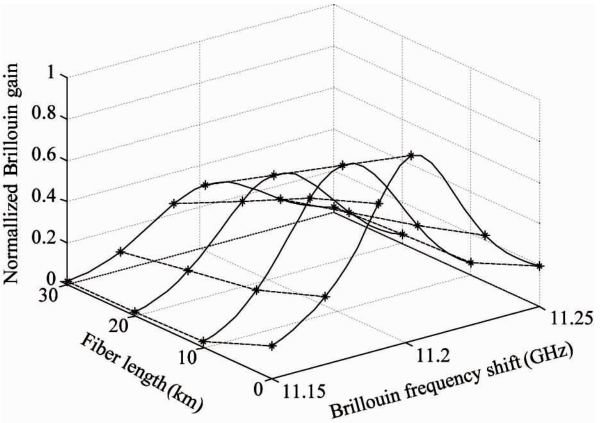



**Fig. 1** Brillouin spectrum measurement based on frequency sweeping

The collected experimental data of the BSS is a set of discrete points, and they are denoted by $(x_i, y_i)$. By fitting the experimental data, BSS basis function $y = f_B(x)$ which is approximating the discrete point distribution can be obtained. The value of each discrete data point corresponding to the abscissa is substituted into the basis function to obtain a set of the amplitude of the optical power of BSS. Fitting degree $R^2$ can be obtained by

$$R^2 = 1 - \frac{\sum_{i=1}^{m}[y_i - f_B(x_i)]^2}{\sum_{i=1}^{m}[y_i - \bar{y}]^2} \quad (2)$$

where $\bar{y}$ is the average of the ordinates of all discrete points. Only when $R^2$ reaches the maximum, the fitting of the experimental data of BSS can reach optimal. This moment, the frequency of the peak value of the base function is BFS.

When the influence of strain on BFS is neglected, BFS is related to temperature as follows[12]:

$$\nu_B(T, 0) = \nu_B(T_0, 0)(1 + C_T\Delta T) \quad (3)$$

where $T$ is the current fiber temperature, $T_0$ is the room temperature, $\Delta T$ is the temperature change, $C_T$ is the temperature coefficient of the BFS and it is 1.18 MHz/℃ in this paper. At $T_0 = 20$ ℃, $v_B$ is 11.203 GHz and it will increase by 1.18 MHz for every 1 ℃ increase in temperature.

## 2 Basic principle of GA-SOA

### 2.1 Principle of GA and SOA

GA is a kind of bionic optimization algorithm which is evolved from the survival rule in nature[13]. GA is used to select crossover and mutation chromosomes directly. Therefore, there is no limit derivation and continuity of function. So GA has some advantages such as parallelism, multivalue comparison and strong robustness.

SOA is a new swarm intelligence algorithm in the field of evolutionary algorithm[14,15].

The search step of SOA is obtained according to the uncertain inference conditions:

$$\alpha_{ij} = \delta_{ij}\sqrt{-\ln(u_{ij})} \quad (4)$$

where $\alpha_{ij}$ is the step size of $j$-dimension search space, $u_{ij}$ is the Gaussian membership, $\delta_{ij}$ is the Gaussian membership function parameters. $\delta_{ij}$ can be obtained by Eqs(5) - (8):

$$u_i = u_{\max} - \frac{s - I_i}{s - I}(u_{\max} - u_{\min}),\ i = 1,2,\cdots,s \quad (5)$$

$$u_{ij} = rand(u_i, 1),\ j = 1,2,\cdots,D \quad (6)$$

$$\vec{\delta}_{ij} = \omega \cdot abs(\vec{x}_{\min} - \vec{x}_{\max}) \quad (7)$$

$$\omega = (T_{\max} - t)/T_{\max} \quad (8)$$

where, $\vec{x}_{\min}$ and $\vec{x}_{\max}$ are the positions of particles with minimum and maximum function values, $I_i$ is the serial number of the population function values in descending order, $D$ is the search space dimension, $s$ is the size of the population, $\omega$ is the inertia weight and decreases with the increase of the evolution algebra, $t$ is the current iterations and $T_{\max}$ is the maximum iterations.

All the factors are considered, and the direction of search is determined by using 3 directions random weighted geometric mean:

$$\vec{d}_i(t) = \mathrm{sign}(\omega\vec{d}_{i,pro} + \varphi_1\vec{d}_{i,ego} + \varphi_2\vec{d}_{i,alt}) \quad (9)$$

where $\vec{d}_{i,pro}$ is the pre-moving direction, $\vec{d}_{i,ego}$ is the direction of self-interest, $\vec{d}_{i,alt}$ is the altruistic direction, $\varphi_1$ and $\varphi_2$ are real numbers which are selected randomly and uniformly in the known interval [0, 1].

After the search direction and step size are determined, the location is updated, and the equation is shown as follows:

$$\Delta x_{ij}(t+1) = \alpha_{ij}(t) d_{ij}(t) \quad (10)$$

$$x_{ij}(t+1) = x_{ij}(t) + \Delta x_{ij}(t+1) \quad (11)$$

where $x_{ij}$ is the particle position, $\Delta x$ is the particle position variation, $d_{ij}$ is the average search direction.

## 2.2 The flow chart of GA-SOA

Compared with the traditional direct search algorithm, SOA can directly simulate the intelligent search behavior of human beings, and its concept is clear and easy to understand. However, in the process of iteration, it often appears that the calculation accuracy becomes lower and it is easy to fall into the local optimal solution. Based on this, GA is introduced into SOA. After updating the population by SOA, GA is used to perform cross-mutation on the particles which are not updated sufficiently. So the information exchange between particles can be carried out and the opportunity to update in wider space can be obtained. In this way, GA can effectively overcome the shortcoming that SOA is easy to fall into the local optimal solution and can not jump out. GA-SOA has fully utilized GA's global search ability and the advantages of easy-to-read and high efficiency of SOA to greatly improve the calculation accuracy.

The algorithm flowchart of GA-SOA is shown in Fig. 2.

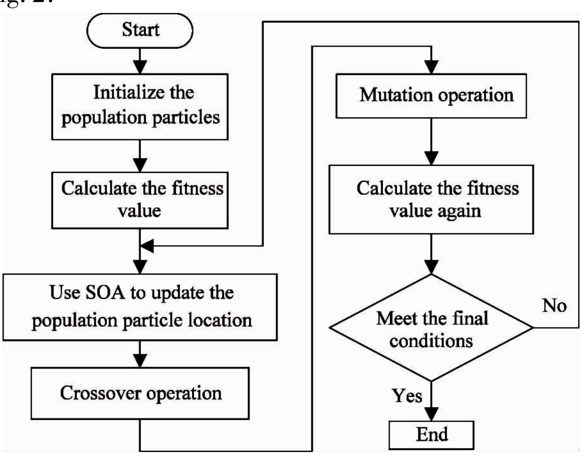
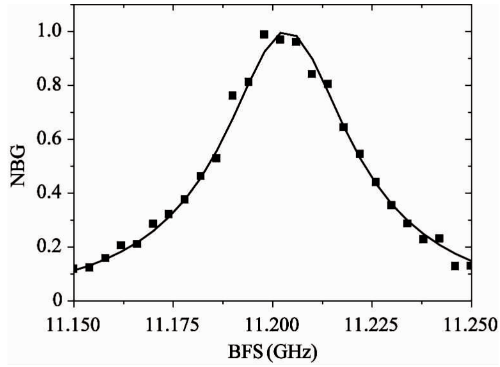


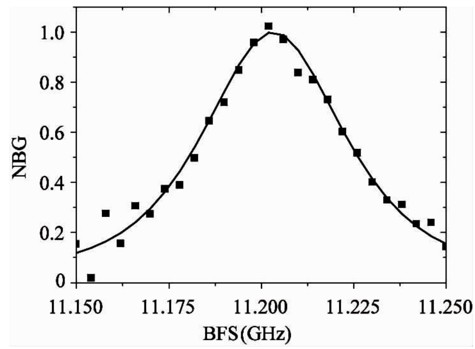

**Fig. 2** The flowchart of GA-SOA

# 3 Simulation analysis of GA-SOA

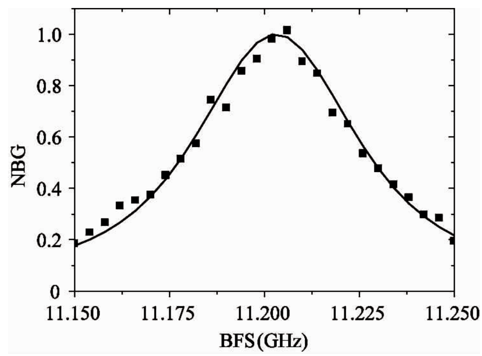
To illustrate that GA-SOA has the feasibility and wide applicability for BSS fitting, data with different linewidth and different linear weight ratio are processed. Suppose that BFS of real curve is 11.203 GHz. $Q$ is the linear weight ratio of the Lorentz line and the Gaussian line in the basis function, and $Q = k/(1-k)$. Assuming that BFS remains unchanged, $Q$ is set to 9:1, 8:2, 7:3, 6:4, as well as the linewidth $\Delta v_{B1}$ is set to 40 MHz, and $\Delta v_{B2}$ are 40 MHz, 60 MHz, 80 MHz, 100 MHz, respectively. In order to simulate the actual measurement environment, the white Gaussian noise is added to the system, and the signal-to-noise ratio (SNR) is 30 dB. The fitting curves are shown in Fig. 3,



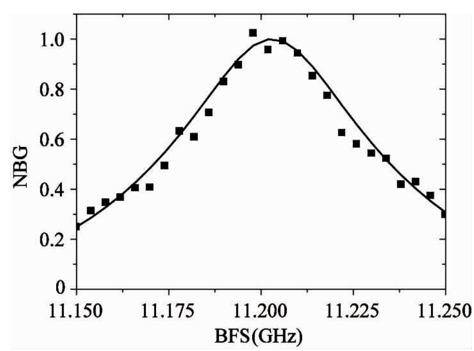

(a) $Q = 9:1$, $\Delta v_{B1} = \Delta v_{B2} = 40$ MHz




(b) $Q = 8:2$, $\Delta v_{B1} = 40$ MHz, $\Delta v_{B2} = 60$ MHz




(c) $Q = 7:3$, $\Delta v_{B1} = 40$ MHz, $\Delta v_{B2} = 80$ MHz




(d) $Q = 6:4$, $\Delta v_{B1} = 40$ MHz, $\Delta v_{B2} = 100$ MHz

**Fig. 3** BSS fitting curve under different conditions where the abscissa is BFS and the ordinate is the normalized Brillouin gain (NBG). The fitting results show that the GA-SOA is feasible for BSS fitting.

$Q$ is set to 9:1, and $\Delta v_{B1}$ is equal to $\Delta v_{B2}$. The data of BSS are generated with different linewidths and different SNRs (e.g. 25 dB, 35 dB and 45 dB) and then are fitted with GA-SOA. The fitting results are shown in Table 1. BFS error is the absolute value of the difference of the real curve and the simulated curve between the two BFS. The results show that the GA-SOA can be used to fit the information of different SNR and linewidth, and high precision BFS and good fitting degree can be obtained.

Table 1 The fitting results under different parameters

| SNR (dB) | Linewidth (MHz) | BFS error (MHz) | Fitting degree $R^2$ |
|---|---|---|---|
| 25 | 40 | 0.4808 | 0.9697 |
| | 60 | 0.4811 | 0.9485 |
| | 80 | 0.3775 | 0.9305 |
| 35 | 40 | 0.2371 | 0.9945 |
| | 60 | 0.4513 | 0.9928 |
| | 80 | 0.4414 | 0.9481 |
| 45 | 40 | 0.1065 | 0.9924 |
| | 60 | 0.3151 | 0.9958 |
| | 80 | 0.2475 | 0.9948 |

Assuming that $\Delta v_{B1} = \Delta v_{B2} = 50$ MHz, $Q$ is set to 9:1, 8:2, 7:3 and SNR are set to 20 dB, 30 dB and 40 dB, respectively. The fitting results of the 4 methods are shown in Table 2. And it shows that GA-SOA is better than the other three algorithms with the same simulation patameters. GA-SOA has the minimum BFS error and the best fitting degree which is 0.0751 MHz and 0.9947, respectively.

Table 2 The fitting results of different algorithms

| $Q$ | SNR (dB) | Algorithm | BFS error (MHz) | Fitting degree $R^2$ |
|---|---|---|---|---|
| 9:1 | 20 | PSO | 0.9601 | 0.8342 |
| | | SOA | 0.8645 | 0.9024 |
| | | GA-QPSO | 0.6719 | 0.9518 |
| | | GA-SOA | 0.2033 | 0.9591 |
| 8:2 | 30 | PSO | 0.9344 | 0.9194 |
| | | SOA | 0.6954 | 0.9378 |
| | | GA-QPSO | 0.4982 | 0.9668 |
| | | GA-SOA | 0.2189 | 0.9887 |
| 7:3 | 40 | PSO | 0.9242 | 0.9826 |
| | | SOA | 0.5524 | 0.9883 |
| | | GA-QPSO | 0.3122 | 0.9779 |
| | | GA-SOA | 0.0751 | 0.9947 |

## 4 Results and discussion

The setup for experiment is shown in Fig. 4. The light generated by a distributed feedback laser diode (DFB-LD) is split into 2 paths by a fiber coupler. One is the reference optical path, the other is the probe optical path, and the coupling ratio of the reference light to the detecting light is 2:98. The probe light is modulated into a pulsed light by an acousto-optic modulator (AOM), and then enters the sensing fiber by an erbium-doped fiber amplifier (EDFA), a polarization controller (PC) and a loop. BSS is generated by the reference light passing through the electro-optic modulator (EOM). EOM is controlled by a microwave source and a DC regulated power supply. The modulated light after passing through the polarization scrambler (PS) is coherent with the Brillouin backscattered light returned from the circulator. The balanced photo-detector (BPD) converts the coherent light signal into the electrical signal. Finally, the experimental data of the BSS is obtained by the digital data acquisition (DAQ) system.

In this experiment, the 30 km long sensing fiber is used with the tail end (1 km) heating in the thermostat and the remaining fiber placing at room temperature of 20 ℃. Under different temperatures, BSS measured by

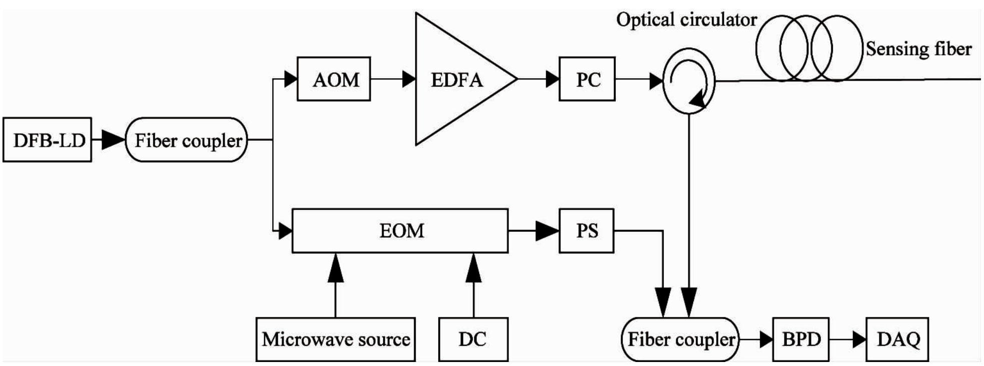
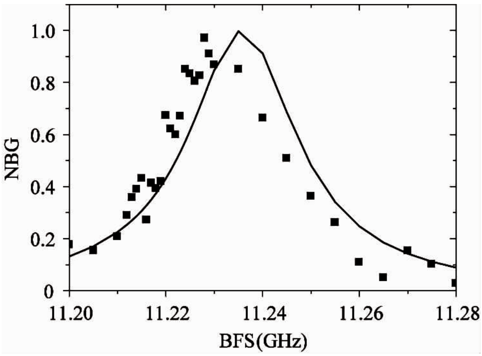
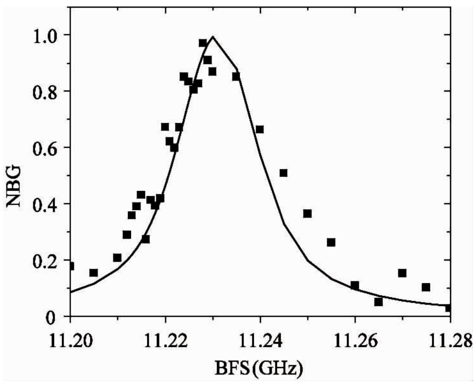



**Fig. 4** The distributed optical fiber sensing detection system based on Brillouin scattering

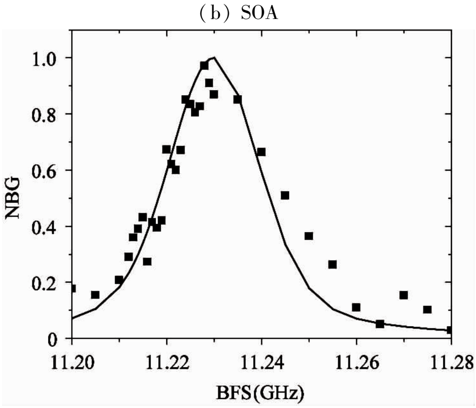
the system is used to collect the data by the way of electronic scanning. In this paper, GA-SOA and PSO, SOA, GA-QPSO are used to compare the temperature data of 3 groups of 25 ℃, 50 ℃ and 80 ℃. Fig. 5, Fig. 6 and Fig. 7 show the fitting curves and Table 3 illustrates the fitting results of experimental data at different temperatures.



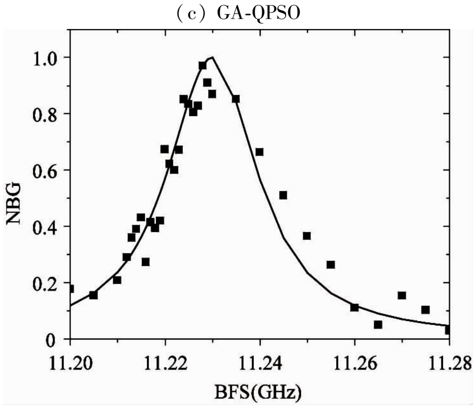
(a) PSO



(b) SOA

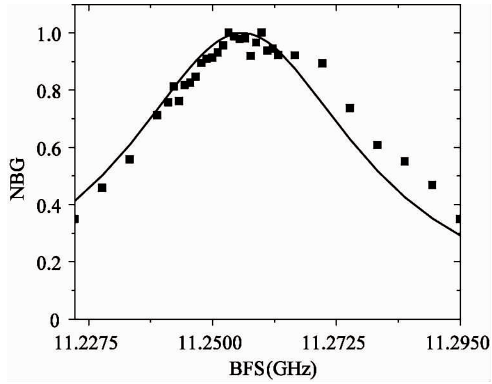


(c) GA-QPSO

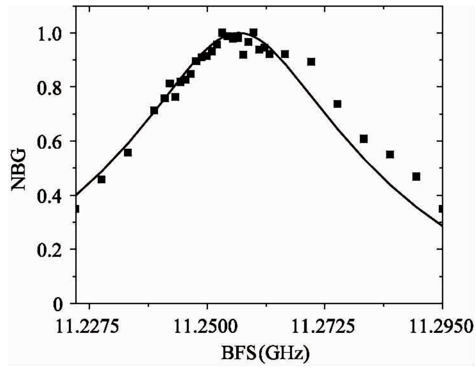


(d) GA-SOA

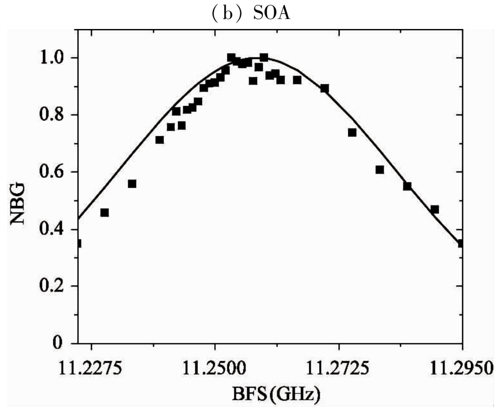
**Fig. 5** The fitting curve of 4 algorithms with 25 ℃



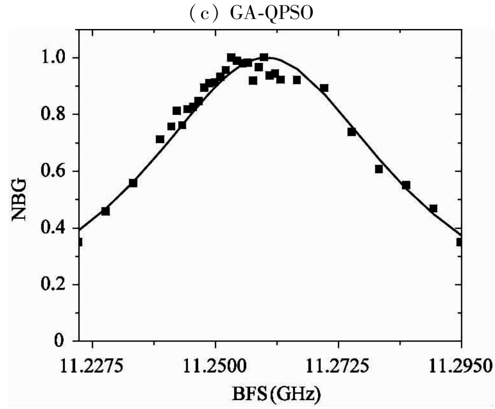
(a) PSO



(b) SOA

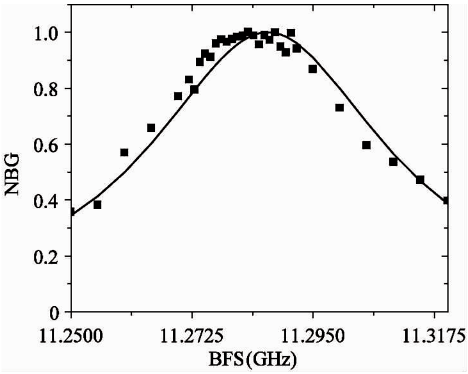


(c) GA-QPSO

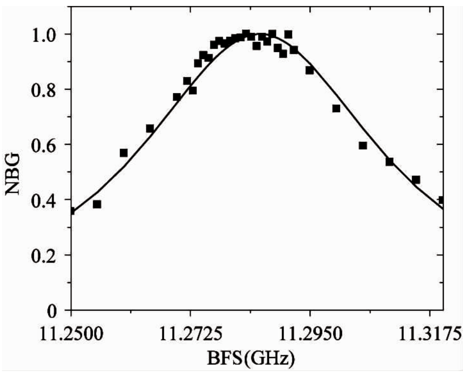


(d) GA-SOA

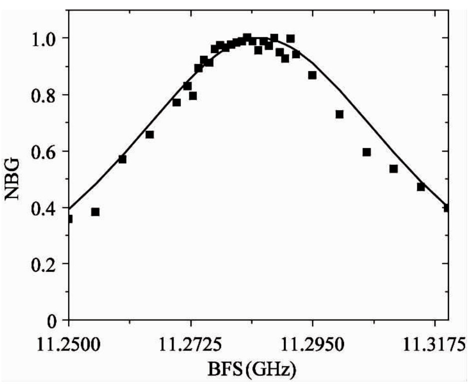
**Fig. 6** The fitting curve of 4 algorithms with 50 ℃



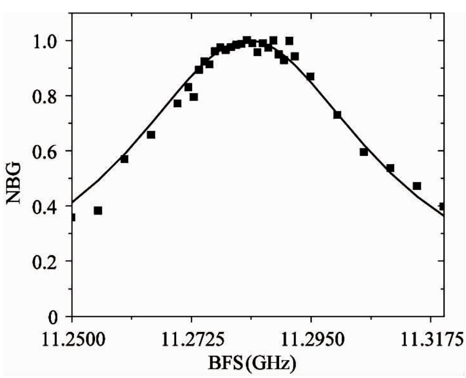
(a) PSO



(b) SOA



(c) GA-QPSO



(d) GA-SOA

**Fig. 7** The fitting curve of 4 algorithms with 80 ℃

From Fig. 5 to Fig. 7 and Table 3, it can be seen that GA-SOA is better than the other three algorithms. In the process of optimization, PSO is easy to fall into local optimum and leads to low precision. QPSO is a new evolutionary optimization algorithm based on the standard PSO by introducing quantum theory into it. It is noteworthy that QPSO has fewer parameters than PSO, but QPSO still has precocious phenomenon. Even after introducing GA, the optimization ability of QPSO is greatly improved, but because of the shortcomings of QPSO itself, the extraction accuracy of GA-QPSO is less than that of GA-SOA. At 3 different temperatures, the minimum BFS error of PSO, SOA and GA-QPSO are 3.591 MHz, 2.542 MHz and 0.921 MHz, respectively; meanwhile, the minimum BFS error of GA-SOA is 0.203 MHz, and the fitting degree is also better than the other three algorithms.

Although SOA can complete the fitting of BSS, but the BFS error is larger and the fitting accuracy is lower because the iterative search algorithm is not fully completed. With increasing iterative times, the convergence speed of the particle population slows down or even stagnates, leading to decrease of the global search ability of SOA, which makes the algorithm fall into local optimal solution easily and end early. Because GA has strong global search ability and adaptability, GA is used to carry out the crossover and mutation operation of the particle which is not fully updated in the SOA. So the information can be exchanged between the particles, and there will be the opportunity to update the location in a broader space, leading to the decreased ability due to the disadvantage of algorithm of global search. Therefore, combining GA with SOA not only accelerates the convergence to the global optimal solution, but also improves the accuracy of fitting algorithm and its BFS is more accurate.

## 5 Conclusion

To summarize, this paper reports a new hybrid optimization method based on GA and SOA to extract Brillouin spectral characteristics. Through the parameter simulation analysis of BSS with different linewidth, different linear weight ratio $Q$ and different SNR, it is found that GA-SOA has small BFS error and high fitting degree. Then the experimental data of BSS at different temperatures are processed by 4 algorithms: GA-SOA, PSO, SOA and GA-QPSO. The results show that the fitting errors of GA-SOA are 0.539 MHz, 0.341 MHz and 0.203 MHz at 25 ℃, 50 ℃, and 80 ℃, respectively. The fitting degrees are 0.928, 0.966 and 0.968, and BFS error and fitting degrees are better than those of other three algorithms. Therefore, GA-SOA can be used to extract BSS information accurately because of its high fitting accuracy and accurate parameter estimation. And further improvement will be made in terms of the extraction accuracy of temperature, strain and other physical information in Brillouin optical fiber sensing system.

Table 3 The fitting results of different algorithms at different temperatures

| Algorithm | BFS error (MHz) | | | Fitting degree $R^2$ | | |
|---|---|---|---|---|---|---|
| | 25 ℃ | 50 ℃ | 80 ℃ | 25 ℃ | 50 ℃ | 80 ℃ |
| PSO | 7. 786 | 3. 649 | 3. 591 | 0. 792 | 0. 903 | 0. 951 |
| SOA | 2. 949 | 2. 916 | 2. 542 | 0. 885 | 0. 928 | 0. 964 |
| GA-QPSO | 1. 899 | 1. 359 | 0. 921 | 0. 891 | 0. 921 | 0. 962 |
| GA-SOA | 0. 539 | 0. 341 | 0. 203 | 0. 928 | 0. 966 | 0. 968 |

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