Analysis of related factors on accuracy in the parameter extraction from Brillouin gain spectrum

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Abstract: Based on the measured Brillouin gain spectrum, the suitable objective function was chosen. According to a large number of numerically generated Brillouin gain spectra, the influences of signal-to-noise ratio (SNR), scanned frequency interval, number of scanned frequency, frequency scanning range, spectra key parameters g_0, v_B and Δv_B on the accuracy in the parameters extracted from Brillouin gain spectrum were systematically investigated. The results indicate that the errors in the extracted parameters exponentially decrease with increasing SNR. The errors in the extracted parameters decrease with increasing number of scanned frequency or decreasing scanned frequency interval. The error in the extracted v_B increases proportionally with Δv_B. However, Δv_B has no influence on the accuracy in the extracted g_0 and Δv_B. If the number of scanned frequency remains constant, then too wide or narrow frequency scanning range will results in significant errors. The optimal frequency scanning range is close to $2\Delta v_B$. This work provides a frame of reference in which you can determine the suitable parameters in Brillouin scattering-based sensing.

Key words: Brillouin gain spectrum; parameter extraction; least-squares method; temperature and strain measurement; accuracy; influencing factors

CLC number: TP212.14 **Document code:** A **DOI:** 10.3788/IRLA201948.0222003

布里渊增益谱特征参数提取准确性影响因素分析

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摘　要: 基于实测布里渊(Brillouin) 增益谱确定了合适目标函数。数值产生了大量的布里渊增益谱,利用这些谱信号系统研究了信噪比、扫频间隔、扫频点数、扫频范围和谱特征参数 g_0、v_B、Δv_B 的取值对布里渊增益谱特征参数提取准确性的影响规律。结果表明:特征参数提取误差随信噪比增加成指数规律下降,随扫频点数增加(或扫频间隔减少)而下降;v_B 的提取误差随 Δv_B 的增加而线性增大,Δv_B 的值对其他参数的提取准确性几乎无影响;扫频点数固定时扫频范围选择太大或太小时的误差均较大,实际应该选择 $2\Delta v_B$ 左右。研究结果对基于布里渊散射的传感时相关参数选择具有参考价值。

关键词: 布里渊增益谱; 参数提取; 最小二乘法; 温度和应变测量; 准确性; 影响因素

收稿日期: 2018-09-05; **修订日期:** 2018-10-10

基金项目: 国家自然科学基金(51607066,61775057);河北省自然科学基金(E2012502045);中央高校基本科研业务费专项(2017MS110)

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0 Introduction

In the fiber Brillouin distributed sensing technology, the dependence of Brillouin gain spectrum on temperature and strain is used to implement sensing. Because of the ability to measure temperature and strain in large infrastructures by use of only one fiber, the distributed optical fiber sensors based on Brillouin scattering have gained significant interest[1-6]. Based on the extracted Brillouin frequency shift and other key parameters, the temperature and strain in the fiber can be obtained. Therefore, how to fit the Brillouin gain spectrum, rapid and highly accurately extract parameters from Brillouin gain spectrum is one of the hottest topics in the field of fiber Brillouin distributed sensing[7-10].

The study about parameters extraction from Brillouin gain spectrum can roughly be separated into two categories: The conventional model based fitting algorithms[7-10] and the non-model based fitting algorithms[11-12]. The former ones are more noise-resistant and are extensively used. Therefore, they are the mainstream algorithms. In 2005, D L Liu et al implement the least-squares method to extract the parameters from the Brillouin gain spectrum. The experiment validates the analysis[7]. In 2009, S H Xiao et al apply the Levenberg-Marquardt algorithm to extract the key parameters which enhanced the accuracy of the built sensing system[8]. In 2014 and 2015, Y J Zhang et al apply the finite element method to modify the Levenberg-Marquardt algorithm and Newton algorithm, and the modified ones are used to extract the key parameters[9-10]. The results indicate that the accuracy of parameters extracted from Brillouin gain spectrum is significantly improved. In comparison with the model based fitting algorithms, the non-model based ones have a greater approximation capability. However, they are overly sensitive to noise which is inevitable in the measured Brillouin gain spectrum. As a result, the non-model based ones are rarely used in practical situations.

In conclusion, the existing works mainly focus on optimization algorithm and its selection. Although they are well studied, the following problems still exist. That is, the different cases correspond to different values of signal-to-noise ratio (SNR), number of scanned frequency, scanned frequency interval, frequency scanning range, g_0, ν_B and $\Delta\nu_B$. They may have a big influence on the accuracy in the extracted parameters. However, the related studies are rarely reported. Therefore, the influence of the above factors on the errors in the extracted parameters should be investigated.

To fix the above problems, according to a typical measured Brillouin gain spectrum, the objective functions are compared and the suitable one is chosen. A large number of Brillouin gain spectra are numerically generated. The influences of SNR, number of scanned frequency, scanned frequency interval, frequency scanning range, g_0, ν_B and $\Delta\nu_B$ on the accuracy in the parameters extracted by the nonlinear model for Brillouin gain spectrum are systematically investigated based on the numerically generated spectra. The suggestions about parameters selection in Brillouin gain spectrum are made.

1 Model selection

1.1 Brillouin gain spectrum

Generally, the injection pulse width is larger than 10 ns, the Brillouin gain spectrum can be modeled by a Lorenzian spectral profile in the frequency domain as:

$$g_B(\nu)=g_0\frac{(\Delta\nu_B/2)^2}{(\nu-\nu_B)^2+(\Delta\nu_B/2)^2} \tag{1}$$

where g_B is dimensionless Brillouin gain, ν is frequency in GHz, g_0 represents the peak value of the Brillouin gain spectrum, ν_B represents the Brillouin frequency shift in GHz, and it characterizes the difference between the central frequency of the Brillouin gain spectrum and the frequency of the incident light. The Brillouin frequency shift of single-mode optical fiber is generally about 11 GHz when the wavelength of incident light is 1 550 nm. $\Delta\nu_B$ represents the 3 dB bandwidth of the Brillouin gain spectrum in GHz and it is relevant to the lifetime of phonon. If the injection pulse width is less than 10 ns, the Brillouin gain spectrum will deviate from the Lorenzian spectral profile and the other spectral profiles should be used[8-11]. However, the influences of related factors on the key parameter extraction errors are quite similar. Therefore, in this work, the Lorenzian spectral profile is used.

1.2 Least-squares model

It is assumed that ν_i and g_{Bi} are the values of the ith scanned frequency and the corresponding measured Brillouin gain, $i=0,1,2,\cdots,N-1$. Based on the least-squares method, the objective function of the parameters extraction problem can be defined as

$$E=\sum_{i=0}^{N-1} e_i^2=\sum_{i=0}^{N-1}(g_B(\nu_i)-g_{Bi})^2 \tag{2}$$

g_0, ν_B and $\Delta\nu_B$ in Eq.(2) are the variables which are needed to be optimized. It is a nonlinear least-squares problem. We can use the Levenberg-Marquardt algorithm to minimize the above objective function. Once the objective function reaches its minimum value, the Brillouin frequency shift, the peak value and the 3 dB bandwidth of the Brillouin gain spectrum can be extracted.

To reduce computational burden, an elegant way can also be used[13]. After some rearranging, Eq.(1) becomes

$$\frac{1}{g_B(\nu)}=\frac{1}{(\Delta\nu_B/2)^2 g_0}\nu^2+\frac{-2\nu_B}{(\Delta\nu_B/2)^2 g_0}\nu+\frac{\nu_B^2}{(\Delta\nu_B/2)^2 g_0}+\frac{1}{g_0} \tag{3}$$

Eq.(3) can be expressed as

$$\frac{1}{g_B(\nu)}=f_B(\nu)=C_1\nu^2+C_2\nu+C_3 \tag{4}$$

where

$$C_1=\frac{1}{(\Delta\nu_B/2)^2 g_0} \tag{5}$$

$$C_2=\frac{-2\nu_B}{(\Delta\nu_B/2)^2 g_0} \tag{6}$$

$$C_3=\frac{\nu_B^2}{(\Delta\nu_B/2)^2 g_0}+\frac{1}{g_0} \tag{7}$$

Let us assume that $V=[V_2,V_1,I]$, $V_2=[\nu_0^2,\nu_1^2,\cdots,\nu_{N-1}^2]^T$, $V_1=[\nu_0,\nu_1,\cdots,\nu_{N-1}]^T$, I is a $N\times1$ column vector with elements of 1, $C=[C_1,C_2,C_3]^T$, and $F=[f_B(\nu_0),f_B(\nu_1),\cdots,f_B(\nu_{N-1})]$. Then we can write Eq.(4) as

$$VC=F \tag{8}$$

The optimization of C in Eq.(8) is a linear least-squares problem and it requires less computational effort. Once C is obtained, g_0, ν_B and $\Delta\nu_B$ can be calculated by use of Eqs.(5)-(7).

1.3 Validation of selected model

In this section, a Corning LEAF (Large Effective Area Fiber) fiber with a length of 9.534 km is used. A typical Brillouin gain spectrum signal is measured by a multi channel optical fiber strain sensing system (N8511, ADVANTEST, Japan). The wavelength of the incident light is 1 550 nm and the pulse width is 200 ns. The scanned frequency interval is 10 MHz, and the scanned frequency range is 10.75 -11 GHz. The number of superposition average of the signal is 2^{11}. The parameters extracted by the two models are summarized in Tab.1. The fitted curves and the measured one are shown in Fig.1.

Tab.1 Computed results of two models for a typical measured signal

Model	g_0	ν_B/GHz	$\Delta\nu_B$/GHz	E
Linear	0.75	10.88	0.06	0.35
Nonlinear	1.07	10.87	0.05	0.02

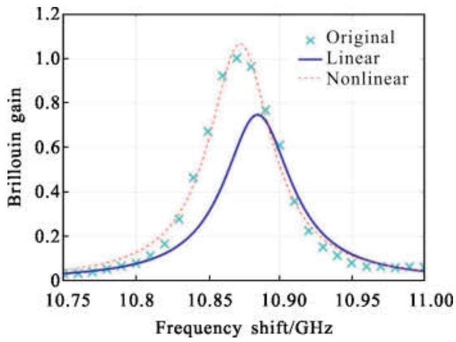

Fig.1 Typical measured signal and corresponding fitted results

According to Fig.1, for the linear model, the fitted curve deviates seriously from the measured

Brillouin gain spectrum signal. Regardless of the peak value or waveform, the nonlinear model is in closer agreement on the results than the linear model. The errors in the parameters extracted by the models are consistent with the fitted errors of the two models. That is, the nonlinear model is appreciably more accurate than the linear model[14].

If ν_B obtained by the nonlinear model is taken as the exact value and ν_B obtained by the linear model has an error of 12.07 MHz. The temperature and strain coefficients are about 1.2 ℃/MHz and 0.05 MHz/$\mu\varepsilon$, respectively. Therefore, the errors in temperature and strain measured by the linear model will be about 10 ℃ and 241 $\mu\varepsilon$, respectively. So, we should choose the nonlinear model to extract the parameters from Brillouin gain spectrum.

This is because different models correspond to different objective functions. The objective function in the nonlinear model is consistent well with the real difference between the fitted curve and the expected one. Therefore, its accuracy is high. The objective function in the linear model is inconsistent with the real difference between the fitted curve and the expected one which is responsible for the fact that the obtained optimal solution may differ strongly from the best result.

2 Analysis of influencing factors

In different practical situations, however, the Brillouin gain spectrum signal is of different values of SNR, number of scanned frequency(Scanned Frequency Interval), frequency scanning range, g_0, ν_B and $\Delta\nu_B$. Therefore, to improve reliability of the analysis results, the influence of various factors on the errors in the extracted parameters needs to be systematically investigated. Unless otherwise stated, g_0, ν_B and $\Delta\nu_B$ are set to 0.7, 10.8 and 0.08 GHz respectively. The frequency is scanned in the interval of $\nu_B-\Delta\nu_B$ to $\nu_B+\Delta\nu_B$. The number of scanned frequency is set to 21. That is, the scanned frequency interval is 8 MHz. The SNR is set to 20 dB. To suppress the influence caused by randomness of the noise, for a certain value of any parameter combination, the signal is numerically generated 10 000 times.

2.1 SNR

There are different noise levels and numbers of superposition average in different cases which lead to different values of SNR for the different sampled signals. The SNR ranges from 0 dB to 40 dB. The mean amplitudes of the relative errors in the three parameters extracted by the nonlinear model are shown in Fig.2.

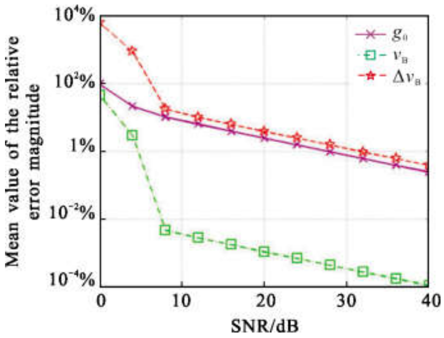

Fig.2 Change of errors in the extracted parameters with SNR

From Fig.2, the errors in the extracted parameters exponentially increase with decreasing SNR. If SNR is less than 20 dB, the error in the model is significant. If SNR is less than 8 dB, the errors in the extracted ν_B and $\Delta\nu_B$ will rapidly increase with decreasing SNR. The error in $\Delta\nu_B$ with SNR =0 dB is considerably larger than the true value. As a result, for the above Brillouin gain spectrum signal, SNR should be larger than 20 dB. Otherwise, the errors in the extracted parameters are significant and results in considerable error in temperature and strain measurement. Certainly, the critical value of SNR will change with other parameters such as the number of scanned frequency and the scanned frequency interval.

2.2 Number of scanned frequency

There are different scanned frequency intervals in different cases. The scanned frequency interval ranges from 1.6 MHz to 40 MHz. Correspondingly, the number of scanned frequency in one $\Delta\nu_B$ varies from 5 to 101. The other parameters are the same as in Section 2.1.

The mean amplitudes of the relative errors in the three parameters extracted by the nonlinear model are displayed in Fig.3 (a). To clearly demonstrate the influence of number of scanned frequency (Scanned Frequency Interval) on the error in the extracted parameters, change of the normalized errors in the extracted parameters with scanned frequency interval is illustrated in Fig.3 (b). The normalized error means that the error for the scanned frequency interval = 1 MHz is normalized to unity.

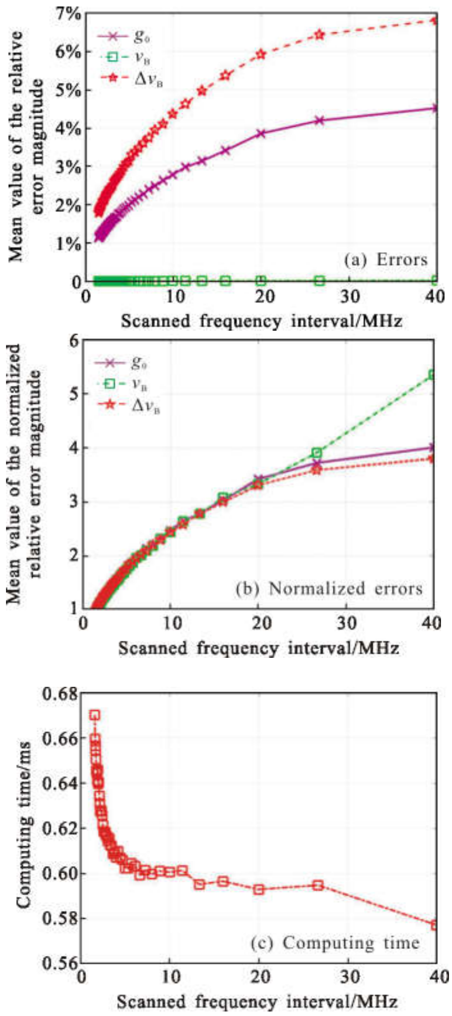

Fig.3 Change of errors in the extracted parameters with scanned frequency interval

From Figs.3(a) and (b) it can be seen that the errors in the extracted parameters decrease with increasing number of scanned frequency (Decreasing Scanned Frequency Interval). The acceleration of error decreases with increasing scanned frequency interval. In contrast, even for very large value of scanned frequency interval, the relative error in the extracted ν_B will increase with increasing scanned frequency interval. If the scanned frequency interval is not more than 20 MHz, that is, one $\Delta\nu_B$ corresponds to not less than 4 scanned frequency points, then all the relative errors in the three parameters are less than 6%. For the relative error, ν_B is of the highest accuracy and $\Delta\nu_B$ is of the lowest accuracy in the nonlinear model. According to Fig.3 (c), the computing time increases with increasing number of scanned frequency (Decreasing Scanned Frequency Interval). However, the rate of change in error is much lower than that of the number of scanned frequency.

2.3 $\Delta\nu_B$

For the conventional single-mode fiber, if the pulse duration is wide, $\Delta\nu_B$ mainly ranges from 0.03 GHz to 0.05 GHz. However, in view of widening and compression of the spectrum, in this section, $\Delta\nu_B$ ranges from 0.01 GHz to 0.15 GHz. The other parameters are the same as in Section 2.1. The mean amplitudes of the relative errors in the three parameters extracted by the nonlinear model are shown in Fig.4(a).

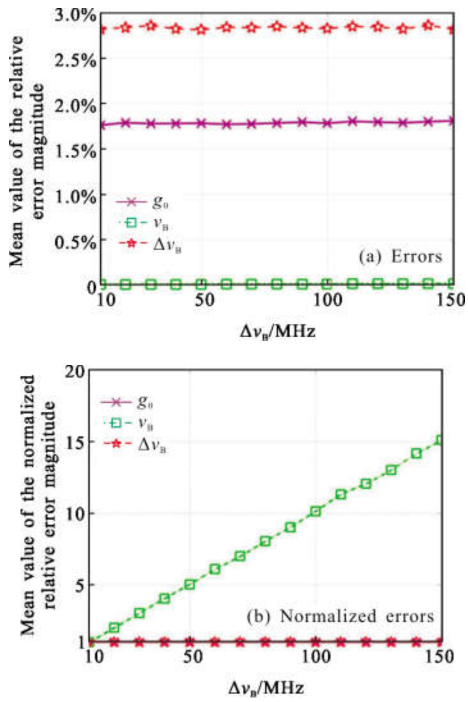

Fig.4 Change of errors in the extracted parameters with $\Delta\nu_B$

From Fig.4(a), it seems that the value of Δv_B has almost no effect on the accuracy of the nonlinear model. All the relative errors in the three parameters are less than 3%. For the relative error, v_B is of the highest accuracy and Δv_B is of the lowest accuracy in the nonlinear model. To clearly demonstrate the influence of Δv_B on the error in the extracted parameters, change of the normalized errors in the extracted parameters with Δv_B is illustrated in Fig.4(b). The normalized error means that the error for the Δv_B=10 MHz is normalized unity. As seen in Fig.4(b) Δv_B has almost no effect on the accuracy of the extracted g_0 and Δv_B. However, the error in the extracted v_B increases proportionally with Δv_B. In Fig.4(a), the error in the extracted v_B is almost independent of Δv_B. This is due to the fact that the error of the extracted v_B is very low and the variation of the error in the extracted v_B cann't be clearly demonstrated in Fig.4(a). The accuracy in the measured temperature and strain depends directly upon the accuracy in the extracted v_B. Therefore, if possible, the experimental setup with lower Δv_B should be used.

2.4 v_B

Based on the fact that the Brillouin frequency shift in different fibers is different and at the same time, it will be influenced by temperature or strain. Therefore, in this section, v_B ranges from 10 GHz to 13 GHz. The other parameters are the same as in Section 2.1. The mean amplitudes of the relative errors in the three parameters extracted by the nonlinear model are shown in Fig.5.

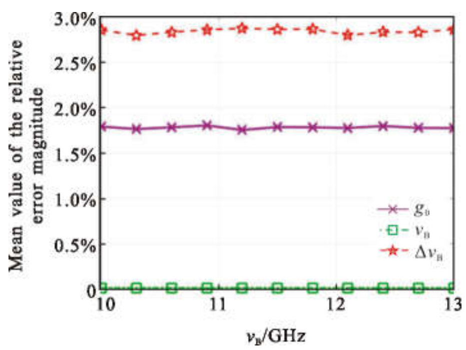

Fig.5 Change of errors in the extracted parameters with v_B

From Fig.5, we can see that the value of v_B has almost no effect on the accuracy of the nonlinear model. All the relative errors in the three parameters are less than 3%. For the relative error, v_B is of the highest accuracy and Δv_B is of the lowest accuracy in the nonlinear model. Because v_B has almost no effect on the errors in the extracted parameters, the normalized errors are not provided in this section.

2.5 g_0

On the basis of the practical situation, g_0 ranges from 0 to 1. The other parameters are the same as in Section 2.1. The mean amplitudes of the relative errors in the three parameters extracted by the nonlinear model are shown in Fig.6.

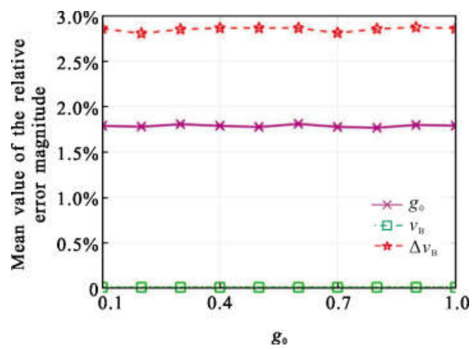

Fig.6 Change of errors in the extracted parameters with g_0

Similar to Fig.5, the value of g_0 in Fig.6 also has almost no effect on the accuracy of the nonlinear model. Similar to Section 2.4, for the relative error, v_B is of the highest accuracy and Δv_B is of the lowest accuracy in the nonlinear model.

2.6 Frequency scanning range

On the basis of the practical situation, the frequency scanning range varies from $\Delta v_B/10$ to $10\Delta v_B$. The other parameters are the same as in Section 2.1. The mean amplitudes of the relative errors in the three parameters extracted by the nonlinear model are illustrated in Fig.7.

According to Fig.7, the frequency scanning range has a great influence on the accuracy in the parameters extracted from Brillouin gain spectrum. The error initially decreases with the frequency scanning range. Once the minimum value of error is reached, it increases with the frequency scanning range. The optimal frequency scanning range is the frequency scanning range corresponding to the minimum error in the parameter extraction. It is apparent that the optimal frequency scanning range in Fig.7 is about $1\Delta\nu_B$–$2\Delta\nu_B$. In this section, we systematically investigate the optimal frequency scanning range in different cases. The SNR ranges from 10 dB to 40 dB and $\Delta\nu_B$ ranges from 0.01 GHz to 0.15 GHz. The number of scanned frequency is set to 7, 15, 31 and 63, respectively. The other parameters are the same as in Section 2.1. The results indicate that the optimal frequency scanning range is close to $2\Delta\nu_B$. That is to say, the Brillouin gain spectrum with a frequency scanning range of about $2\Delta\nu_B$ should be chosen to extract parameters.

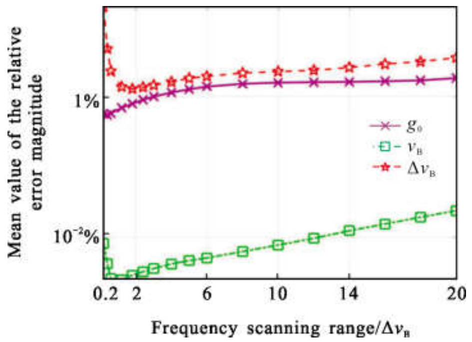

Fig.7 Change of errors in the extracted parameters with frequency scanning range

3 Conclusion

The comparison of the two models is conducted for a typical measured Brillouin gain spectrum signal and the better nonlinear model is chosen. The influence of SNR, number of scanned frequency (scanned frequency interval), frequency scanning range, g_0, ν_B and $\Delta\nu_B$ on the accuracy in the parameters extracted by the nonlinear model for Brillouin gain spectrum are systematically investigated.

The results indicate that: The errors in the extracted parameters exponentially decrease with increasing SNR. The errors in the extracted parameters decrease with increasing number of scanned frequency (Decreasing Scanned Frequency Interval). The error in the extracted ν_B increases proportionally with $\Delta\nu_B$. However, $\Delta\nu_B$ has no influence on the accuracy in the extracted g_0 and $\Delta\nu_B$. If the number of scanned frequency remains constant, too wide or narrow frequency scanning range corresponds to significant errors. The optimal frequency scanning range is close to $2\Delta\nu_B$. The values of ν_B and g_0 have no effect on the accuracy of the nonlinear model.

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