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Characteristics of amplified spectrum of a weak frequency-detuned signal in a Brillouin amplifier

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Abstract

We will theoretically and experimentally study the effect of the linewidth and the frequency of a weak detuned signal on its amplified spectrum in the Brillouin amplifier. We will show that the spectral profile of the input signal is preserved during amplification only when the signal linewidth is much narrower than the Brillouin linewidth of the amplifier. If the signal linewidth is near or above the Brillouin linewidth, the frequency shift of the amplified signal with respect to the pump will be close to the Brillouin shift of the amplifier, and will be independent of the frequency shift of the input signal.

Keywords: Amplified signal spectrum; Brillouin amplification; Frequency detuning; Stimulated Brillouin scattering

1. INTRODUCTION

In recent years, stimulated Brillouin scattering (SBS) has received considerable attention because it has a broad range of applications (Kong *et al.*, 2007, 2009; Ostermeyer *et al.*, 2008; Shi *et al.*, 2008; Wang *et al.*, 2007; Hasi *et al.*, 2007, 2008; Meister *et al.*, 2007; Yoshida *et al.*, 2007). Especially, the Brillouin amplifier can amplify a weak signal with high gain (Glick & Sternklar, 1995; Bel'dyugin *et al.*, 2005). Therefore, it has potential applications in the lidar and optical communication system. To achieve high-gain amplification or enhance power load, Brillouin amplification in different media has been presented. Hasi *et al.* (2007) reported that the power load of the generator cell was enhanced by using the amplifier medium with small absorption rate, and the generator medium with high optical breakdown threshold. According to the characteristic that the Brillouin shift of CS_2 is near to that of water, Gao *et al.* (2008*a*) reported Brillouin amplification of weak Stokes signals from water, obtaining the signal gain of $\sim 10^8$ for the signal energy of 1pJ by using CS_2 as the amplifier. Jones *et al.* (1995) observed experimentally that the range of signal frequency detuning over which a Brillouin amplifier yields high gain was extended for a spectrally broadened signal. In the above researches, the frequency difference between the pump and the signal beams is not equal to the Brillouin shift of the amplifier, which can cause the input signal to be detuned in frequency away from the peak of the Brillouin resonance. In practical applications, if the amplifier medium is chosen, the signal may be detuned owing to the change of external environment such as the water temperature, moving objects, and so on. The characteristics of amplified spectrum of this detuned signal are of great importance for the detection and processing of the signal. However, few investigations on the correlation between spectral characteristics of the amplified signal and those of the input signal have been performed.

In this paper, we numerically study the response of the intensity and the spectral profile of the amplified signal to the frequency and linewidth of the input signal. The simulated results indicate that when the frequency of a weak input signal is shifted in the amplification bandwidth, for a narrow-linewidth signal (i.e., the signal linewidth is much narrower than the Brillouin linewidth of the amplifier), the frequency and linewidth of the amplified beam are the same as those of the input signal; whereas for a wide-linewidth signal (the signal linewidth is near or above the Brillouin linewidth), its amplified beam has a fixed central frequency, which is independent on the frequency of the input signal. We have performed experimental measurements which confirm some of our theoretical predictions.

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2. THEORY

We assume the pump and the signal beams counter-propagating within the Brillouin amplifier. For a sufficiently weak signal, the transient SBS coupled wave equations in the undepleted pump regime are written as (Zhu & Gauthier, 2005)

$$\frac{\partial E_S}{\partial z} + \frac{n}{c}\frac{\partial E_S}{\partial t} = \mathrm{i}g_1\rho^* E_P - \frac{1}{2}\alpha E_S, \tag{1a}$$

and

$$\frac{\partial \rho}{\partial t} + \left(\frac{1}{2}\Gamma - \mathrm{i}\Delta\omega\right)\rho = \mathrm{i}g_2 E_P E_S^*, \tag{1b}$$

where E_P, E_S, and ρ are the amplitudes of the pump, the signal, and the acoustic waves, respectively; n is the refractive index of the medium; g_1 and g_2 are the coupling coefficients; α is the absorption coefficient; $\Gamma = 1/\tau$ denotes the phonon decay rate, where τ is the phonon lifetime; $\Delta\omega = \omega_B - \omega_{sin}$ is the frequency detuning of the signal wave from the SBS gain line-center; ω_B is the Brillouin shift of the medium; $\omega_{Sin} = \omega_{P0} - \omega_{S0}$ is the frequency shift of the input signal, where ω_{P0} and ω_{S0} are the center angular frequencies of the pump and the signal waves.

Assuming that the pump wave is a monochromatic beam and transforming Eq. (1) into the frequency domain, we obtain

$$\frac{\partial \tilde{E}_S}{\partial z} + \frac{\mathrm{i}(\omega - \omega_{Sin})n}{c}\tilde{E}_S = -\mathrm{i}g_1\tilde{\rho}^* E_P + \frac{\alpha}{2}\tilde{E}_S, \tag{2a}$$

and

$$\left[\frac{1}{2}\Gamma + \mathrm{i}(\omega - \omega_B)\right]\tilde{\rho} = \mathrm{i}g_2 E_P \tilde{E}_S^*, \tag{2b}$$

where $\tilde{E}_S$ and $\tilde{\rho}$ are the Fourier transformations of E_S and ρ. Substituting ρ from Eq. (2b) to Eq. (2a) yields

$$\frac{\partial \tilde{E}_S}{\partial z} = -\frac{\mathrm{i}(\omega - \omega_{Sin})n}{c}\tilde{E}_S - \frac{g_1 g_2 |E_P|^2 \tilde{E}_S}{\frac{1}{2}\Gamma - \mathrm{i}(\omega - \omega_B)} + \frac{\alpha}{2}\tilde{E}_S. \tag{3}$$

Solving (3) gives the amplified signal spectrum:

$$I_{Sout}(\omega) = I_{Sin}(\omega)\exp\left[\frac{g\left(\frac{\Gamma}{2}\right)^2 I_P L}{\left(\frac{1}{2}\Gamma\right)^2 + (\omega - \omega_B)^2}\right]\exp(-\alpha L), \tag{4}$$

where L is the interaction length, $I_P = (nc/8\pi)|E_p|^2$ is the pump intensity, $g = 32\pi g_1 g_2/nc\Gamma$ is the Brillouin gain coefficient. The input signal beam with a Gaussian frequency spectrum, $I_{Sin}(\omega)$, is given by

$$I_{Sin}(\omega) = I_{Sin}(\omega_{Sin})\exp\left[-4\ln 2\left(\frac{\omega - \omega_{Sin}}{\Delta\omega_{Sin}}\right)^2\right], \tag{5}$$

where $\Delta\omega_{Sin}$ is the linewidth of the signal beam. The total amplified signal intensity integrated over its spectrum, I_{Sout}, is then given by

$$I_{Sout} = \int_{-\infty}^{\infty} I_{Sout}(\omega)\mathrm{d}\omega. \tag{6}$$

In the following numerical analysis, the simulation parameters are the pump intensity I_P of 15 MW/cm^2, the total intensity I_{Sin} of the input signal of 10^{-9} MW/cm^2, the laser wavelength of 532 nm, and the interaction length of 20 cm. The main medium parameters are listed in Table 1, where ν_B (=$\omega_B/2\pi$) and $\Delta\nu_B$ denote the Brillouin shift and Brillouin linewidth, respectively. Figure 1 shows the total amplified signal intensity, I_{Sout}, and the signal gain *versus* the frequency detuning $\Delta\nu(=\Delta\omega/2\pi)$ for various linewidths of the input signals (using CS_2 as the amplifier medium). The signal gain is taken to be the ratio of I_{Sout} to I_{Sin}. We see that a detuned signal can still be efficiently amplified if the frequency detuning $\Delta\nu$ is controlled in certain range. The narrow-linewidth signal has the higher amplification than the wide-linewidth one near the frequency matching, since its different spectral components can be amplified with approximately maximum gain. However, the output of the wide-linewidth signal will be stronger than that of the narrow linewidth if the detuning exceeds a certain value in the amplification bandwidth. This is due to the higher intensity in the wings of the wide-linewidth signal spectrum. Therefore, the detuning range over which yields high amplification increases as the signal linewidth $\Delta\nu_{Sin}$ is increased. This result is consistent with the experimental results reported (Jones *et al.*, 1995).

The signal linewidth has the effect not only on the amplified signal intensity but also on its frequency shift and linewidth. Figure 2 shows the amplified signal spectra (ASS) for different signal linewidths, taking CS_2 for example. The frequency shift of the signal beam, $\nu_{Sin}(=\omega_{Sin}/2\pi)$, is 7.60 GHz. The detuning $\Delta\nu$ is 0.14 GHz. It can be seen that the frequency shift ν_{Sout} of the ASS changes from ν_{Sin}

Table 1. *The parameters of some SBS media at 532 nm*

Medium	n	ν_B (GHz)	$\Delta\nu_B$ (GHz)	g (cm/GW)	τ (ns)
CS_2	1.63	7.74[a]	0.2[b]	68	1.59[b]
FC-72	1.25	2.39[a]	1.08[b]	6	0.29[b]

[a] The parameters of the media are measured in the experiment; [b] The parameters are calculated according to the equation given by Erokhin *et al.* (1986) and the results at 1064 nm (Erokhin *et al.*, 1986; Yoshida *et al.*, 1997); Others are quoted from Erokhin *et al.* (1986) and Yoshida *et al.* (1997).

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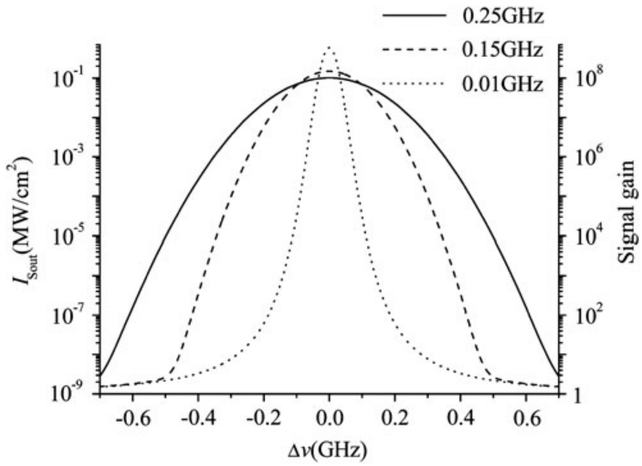

Fig. 1. Amplified signal intensity I_{Sout} and signal gain versus the frequency detuning $\Delta\nu$ for the linewidths of the input signals $\Delta\nu_{Sin} = 0.25$ GHz, 0.15 GHz, 0.01 GHz.

to the Brillouin shift ν_B with increasing signal linewidth $\Delta\nu_{Sin}$. For the case of $\Delta\nu_{Sin}/\Delta\nu_B = 0.05$, the ASS has the same frequency shift and linewidth as the input signal, since every spectral component of the signal beam experiences an approximately uniform gain due to the very narrow linewidth. At $\Delta\nu_{Sin}/\Delta\nu_B = 0.3$, the ASS has a distorted spectral line-shape. As the signal linewidth is increased, its spectral components will be non-uniformly amplified. The components near the resonant region have higher gain; therefore, the ASS peak is pulled toward ν_B. When $\Delta\nu_{Sin}/\Delta\nu_B = 1$, compared with $\Delta\nu_{Sin}$, the ASS linewidth $\Delta\nu_{Sout}$ obviously narrows. The component that is resonant with the Brillouin interaction dominates over other components owing to the maximum gain.

We also calculate ν_{Sout} as a function of $\Delta\nu_{Sin}/\Delta\nu_B$ for different signal frequency shifts using available common SBS media as the amplifiers. Figure 3 only gives the results of two typical media of FC-72 and CS_2. By analyzing the calculated data, we find that when $\Delta\nu_{Sin}/\Delta\nu_B \sim 0.1$, $(\nu_{Sout} - \nu_{Sin})/\nu_{Sin}$ is usually less than or near 5%, and at this time ν_{Sout} can be considered to be near ν_{Sin}. Therefore, for the case of $\Delta\nu_{Sin} \ll \Delta\nu_B$, amplified beams essentially retain their original spectrum parameters. If $\Delta\nu_{Sin}/\Delta\nu_B \sim 1$, ν_{Sout} will be close to ν_B and will be independent of ν_{Sin}. For the case of $\Delta\nu_{Sin}/\Delta\nu_B$ between 0.1 and 1, ν_{Sout} depends on ν_{Sin} and is between ν_{Sin} and ν_B. The same conclusions can be obtained for other nonlinear media as well.

3. EXPERIMENT

The experimental setup is shown in Figure 4. The laser used is an injection-seeded, Q-switched, and pulsed Nd:YAG laser (Continuum Powerlite Precision II 9010) with a linewidth of 90 MHz and repetition rate of 10 Hz. After

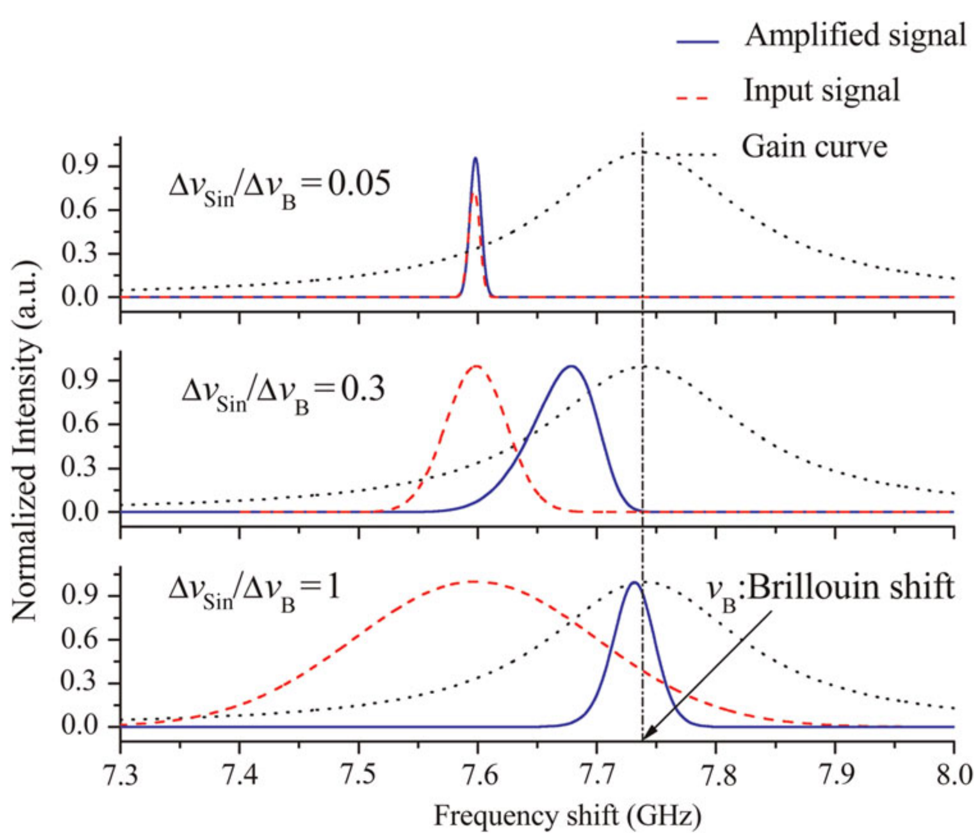

Fig. 2. (Color online) Amplified signal spectrum ASS for $\Delta\nu_{Sin}/\Delta\nu_B = 0.05, 0.3, 1$.

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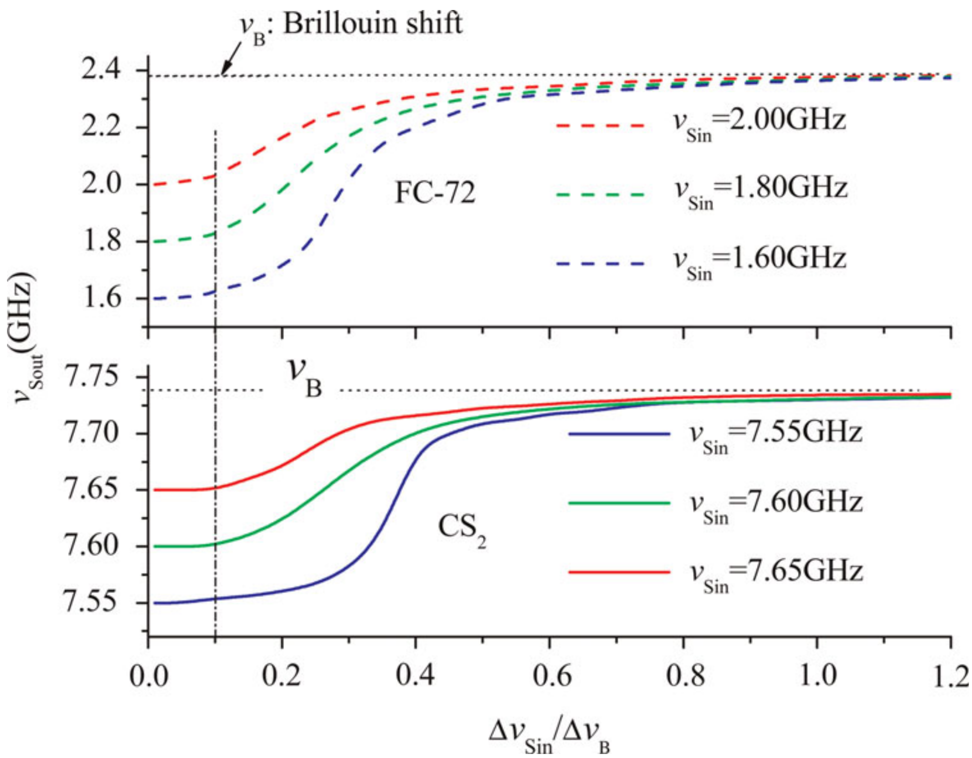

Fig. 3. (Color online) Frequency shifts ν_{Sout} of amplified signals versus $\Delta\nu_{Sin}/\Delta\nu_B$ for different input signal shifts ν_{Sin}.

frequency doubling, the output wavelength is 532 nm, and the pulse width is 7–8 ns. The beam from the laser initially has s-polarization. It passes through a half-wave plate, and is split into two beams by polarizer P_1. The reflected beam is focused into the generator cell (BG). The retuning SBS beam is used as a signal beam. The transmitted beam from polarizer P_1 is used to form a pump beam. These two beams collinearly interact in the 20 cm-long Brillouin amplifier (BA). The diameter of the pump is 8 mm at the entrance of the cell, while the signal beam has the diameter of 6 mm. The amplified signal beam reflected by polarizer P_3 is overlapped with a portion of the pump beam reflected by 4% beam splitter (BS_1), and is directed toward the confocal scanning Fabry-Perot interferometer (F-P, Burleigh SA^{PLUS}) with a free spectral range (FSR) of 2 GHz (the maximum resolution is 6.7 MHz). For measuring the frequency shift of the signal, we insert a baffle between BS_1 and P_3, and hence the signal and pump beams are directed into the F-P.

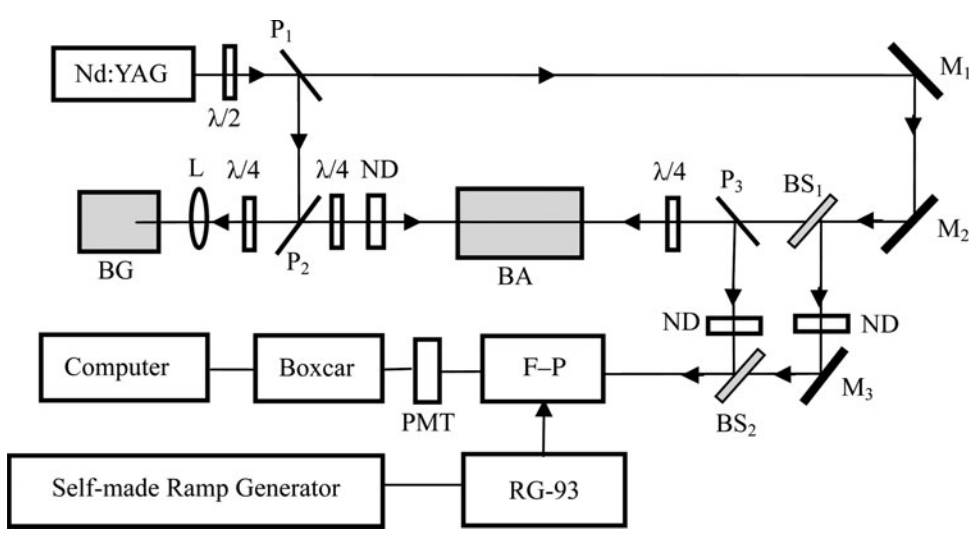

Fig. 4. Experimental setup: BG, Brillouin generator; BA, Brillouin amplifier; P's, polarizers; ND, neutral-density filer; M's, mirrors; L, lens; BS's, beam splitter; F–P, scanning Fabry–Perot interferometer; PMT, photomultiplier tube.

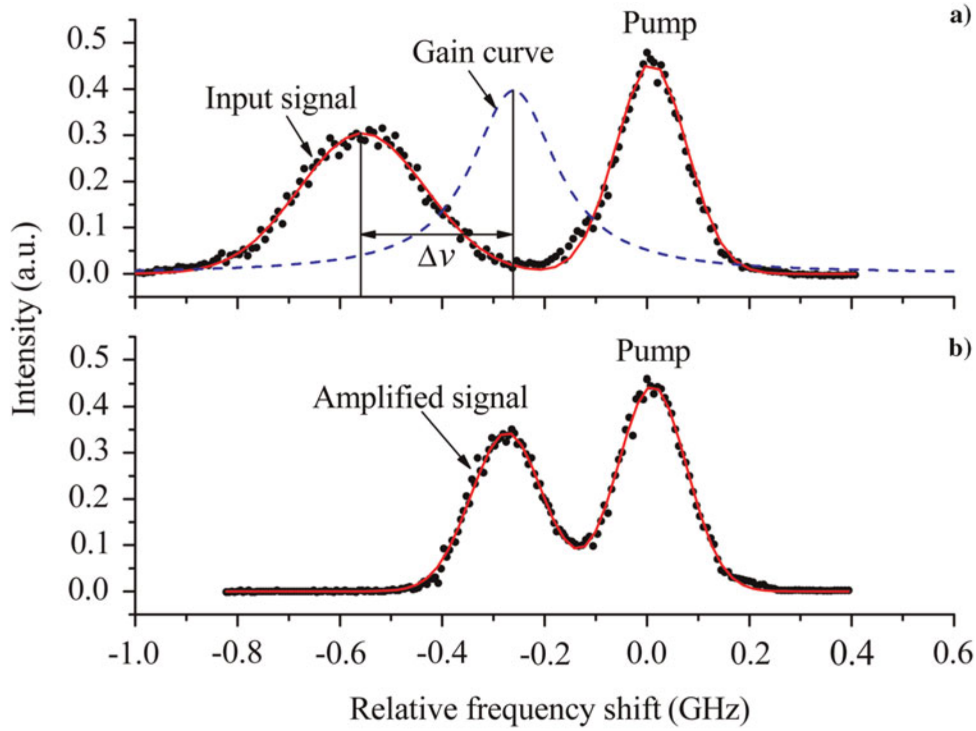

Fig. 5. (Color online) Spectra of the input signal (**a**) produced by 90%CS_2 and 10%CCl_4 and its amplified signal (**b**) as well as the pump beam. Because of the low FSR the frequency shift of the input and amplified signal can be determined by subtracting the measured shift from 8 GHz.

The interferometer is driven by the device (Burleigh RG-93) controlled by self-made ramp generator with a 500-s scanning period (Gao *et al.*, 2008*b*). The signal detected by a CR115 photomultiplier tube (PMT) is integrated and averaged over 10 laser shots by a gated integrator and Boxcar averager (Stanford Research System SR-250). Before experiments, we blocked a signal beam and only directed a pump beam into the amplifier cell, and did not find self-SBS spectrum of the medium.

Theoretical predictions of the amplified spectrum for a narrow-linewidth signal have been validated by comparing them with the experimentally measured Brillouin gain spectrum based on pump-probe technique in the optical fiber (Nikles *et al.*, 1997). Therefore, we focus on the case of a wide-linewidth signal and study the dependence of the amplified spectrum on the input signal frequency. CS_2/CCl_4 mixture is chosen as the generator medium. By varying the fraction of CS_2 in CCl_4, the input signal frequency is changed. CS_2 is used as the amplifier medium. The volume fractions Φ of CS_2 are 95%, 90%, 85%, and 80%, respectively. The signal energy is attenuated to 1 nJ by the neutral density filters (ND). The pump energy is 55 mJ. In order to accurately measure the spectral change, we first measured the input and the output signal spectra by using the interferometer with 8 GH FSR and determined their frequency shift range from 7 GHz to 8 GHz. We then replaced the 8 GHz FSR mirror set with the 2 GHz FSR one. Because of the low FSR, the frequency shift of the input and amplified signal can be determined by subtracting the measured shift from 8 GHz. Figure 5 shows the input signal (a) and its amplified spectrum (b) at $\Phi = 90\%$. The aim to introduce the pump beam is to compare the frequency shift before amplification with that after amplification. The solid lines are the fitted curves by Gaussian functions. We see that the frequency shift of the amplified beam is closed to the Brillouin shift of the amplifier, and the linewidth becomes narrow with respect to the input signal. The signal spectra generated by mixture media with other volume fraction and corresponding amplified spectra are similar to those shown in Figure 5. Their frequency shifts and linewidths are listed in Table 2. According to the experimental conditions and taking into account the convolution correction of the pump bandwidth (Herráez *et al.*, 2006);

Table 2. *Comparison of measured and calculated frequency shifts* ν_{Sout} *and linewidths* $\Delta\nu_{Sout}$ *of amplified beams for different signal frequency shifts*

Φ (%)	ν_{Sin} (GHz)	ν_{Sout}^{exp} (GHz)	ν_{Sout}^{theor} (GHz)	$\Delta\nu_{Sin}$ (GHz)	$\Delta\nu_{Sout}^{exp}$ (GHz)	$\Delta\nu_{Sout}^{theor}$ (GHz)
95	7.55	7.73	7.73	0.23	0.13	0.11
90	7.44	7.72	7.73	0.25	0.13	0.11
85	7.35	7.72	7.73	0.26	0.14	0.11
80	7.25	7.72	7.73	0.27	0.15	0.12

we obtain the theoretically predicted values of the frequency shifts and linewidths of amplified beams, as shown in Table 2. As seen the frequency shifts of amplified beams are independent of those of input signals. Experimental results agree with the theoretical predictions.

4. CONCLUSION

We have shown that the intensity and spectral profile of the amplified signal depend on the frequency and linewidth of the input signal. First, for the case in which the signal linewidth is much less than the Brillouin linewidth of the amplifier, the linewidth and the frequency of the input signal are essentially preserved. Hence, this case is suitable for beam amplification applications to measure the change of the frequency or linewidth of the weak signal. Second, if the signal linewidth is near or above the Brillouin linewidth, the amplified spectrum will narrow, and its frequency shift will close to the Brillouin shift of the amplifier. Moreover, the amplification bandwidth will be increased. This result has implications in the detection of moving objects. Finally, when the signal linewidth is between the two cases mentioned above, the amplified spectrum presents the aberration such as the asymmetric profile. The simulated results have been validated experimentally for the cases of the narrow- and wide-linewidth signals.

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