Research on stimulated Brillouin scattering suppression based on multi-frequency phase modulation

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The method of generating equal-amplitude spectral lines by multi-frequency phase modulation is used in stimulated Brillouin scattering (SBS) suppression. The spectra of three, five, seven, and eleven equal-amplitude spectral lines are obtained in experiment with flatnesses less than 0.3 dB. Theoretical research on SBS suppression shows that the threshold power after modulation is in reverse proportion to the maximum square of amplitude moduli of fundamental frequency and the nth harmonic wave. The threshold powers of three, five, seven, and eleven equal-amplitude spectral lines are improved by 5.21, 8.36, 9.39, and 10.76 dB, respectively.

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There are many nonlinear phenomena in optical fibers including stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS), four-wave mixing, self-phase modulation, and cross-phase modulation[1]. Among them, SBS is a nonlinear phenomenon that transfers optical power of forward optical transmission signal to backward scattered light and phonon field. Compared with other nonlinear phenomena in optical fibers, SBS is the easiest one to happen due to its lowest threshold power. SBS in optical fibers will cause the loss of optical signals and result in the decrease of signal-to-noise ratio (SNR) in the receiver, which will greatly damage the performance of optical transmission system. In order to avoid SBS, the fiber-entering power must be limited under the SBS threshold, which obstructs the improvement of the system performance. The methods to suppress SBS in optical fibers include high frequency dithering[2], phase modulation[3], and dispersion compensation[4]. However, due to the high cost of Raman amplifier, dispersion compensation can only be applied under special circumstances[5]. The high frequency dithering method is to add extra amplitude modulation to a laser beam using a signal of high frequency and low amplitude. The SBS threshold will be increased because the chirp effect of laser frequency will broaden the spectrum of the emission beam. However, this method causes other problems such as additional dispersion phenomenon[1]. Phase modulation is to add extra phase modulation to the beam before or after the usual amplitude modulator. This method distributes energy of optical signal to a great amount of optical side frequency waves to reduce the energy density of optical power spectra and to increase SBS threshold. However, present phase modulation is mainly about single frequency and does little to the increase of SBS threshold with about 5 dB[1]. Some proposed to do a second modulation[6], but the high level nth harmonic wave will superpose the spectral lines of the first modulation and influence the equal-amplitude feature. This will compromise the effect of suppression in a great deal.

In this letter, we conduct the numerical and experimental research on the equal-amplitude spectral lines based on multi-frequency phase modulation. We obtain three, five, seven, and eleven equal-amplitude spectral lines in experiment. The research on the suppression of SBS in optical fiber is conducted on the basis of the obtained equal-amplitude spectral lines. The SBS threshold of three, five, seven, and eleven equal-amplitude spectral lines are obtained. In this research, only one phase modulator is used. The equipment is simple and the experiment is easily carried out. There is no superposition problem of second modulation, and the equal-amplitude feature of the spectral lines is fine.

It was mentioned in Ref. [7] that when modulating in single frequency with the index $\gamma = 1.435$, only three equal-amplitude spectral lines can be obtained. The multi-frequency phase modulation must be adopted in order to obtain more equal-amplitude spectral lines. As for an arbitrary modulation signal $m(t)$ with a period of f_{m}, its Fourier expansion is given by

$$m(t) = \sum_{k=0}^{+\infty} \gamma_k \sin(2\pi k f_{\mathrm{m}} t + \phi_k). \qquad (1)$$

With this modulation signal, the complex amplitudes of the fundamental frequency and side frequencies are given by[8]

$$\begin{cases} A_0 = \sum\limits_{\sum_{k=1}^{+\infty} k\cdot n_k=0} \prod_{k=1}^{+\infty} J_{n_k}(\gamma_k, \phi_k) \\ A_i = \sum\limits_{\sum_{k=1}^{+\infty} k\cdot n_k=i} \prod_{k=1}^{+\infty} J_{n_k}(\gamma_k, \phi_k) \\ A_{-i} = \sum\limits_{\sum_{k=1}^{+\infty} k\cdot n_k=-i} \prod_{k=1}^{+\infty} J_{n_k}(\gamma_k, \phi_k) \end{cases}$$

$$i = 1, 2, 3, \cdots, \qquad (2)$$

where A_0 is the complex amplitude of the fundamental frequency, A_i and A_{-i} are the complex amplitudes of upper and lower ith side frequencies, respectively.

The parameters of modulation signals for five, seven, and eleven equal-amplitude spectral lines are shown in Table 1, where N is the number of equal-amplitude spectral lines.

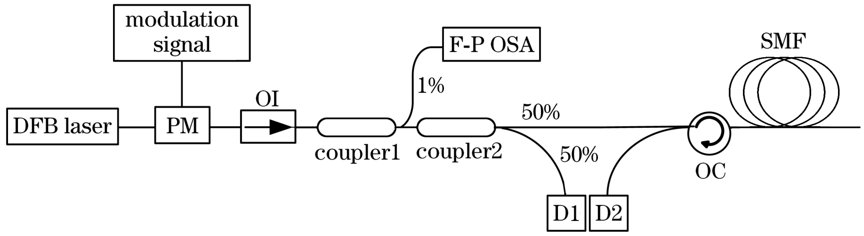

Fig. 1. Experimental setup of SBS suppression based on multi-frequency phase modulation. PM: phase modulator; OI: optical isolator.

Table 1. Parameters of Modulation Signals for Different Numbers of Equal-Amplitude Spectral Lines

γ_1	γ_2	ϕ_2	γ_3	ϕ_3	γ_5	ϕ_5	N
1.240	1.531	0.5π					5
1.386			1.432	0.506π			7
1.650			0.724	0.995π	1.404	0.48π	11

The experimental setup is shown in Fig. 1. A narrow linewidth distributed feedback (DFB) fiber laser at 1550.12 nm was used as the optical source. An arbitrary function generator (AFG) was used to generate the required modulation signal, which was then amplified to the required amplitude before applied to phase modulator. We chose a frequency of 30 MHz as the fundamental frequency. The spectra of modulated lightwave were measured by a Fabry-Perot (F-P) optical spectrum analyzer (OSA) with a free spectrum range of 2 GHz and a resolution of 7 MHz. The measured half-wave voltage of phase modulator was 8.3 V. The experimental spectra of three, five, seven, and eleven equal-amplitude spectral lines are shown in Fig. 2, and their flatnesses are of 0.06, 0.13, 0.17, and 0.29 dB, respectively.

If we use P_0 to represent the threshold power of SBS without modulation, then the threshold after modulation can be obtained by

$$P = P_0 \cdot \frac{1}{\max|A_i|^2}. \quad (3)$$

According to Eq. (3), the threshold after modulation is in reverse proportion to the maximum square of

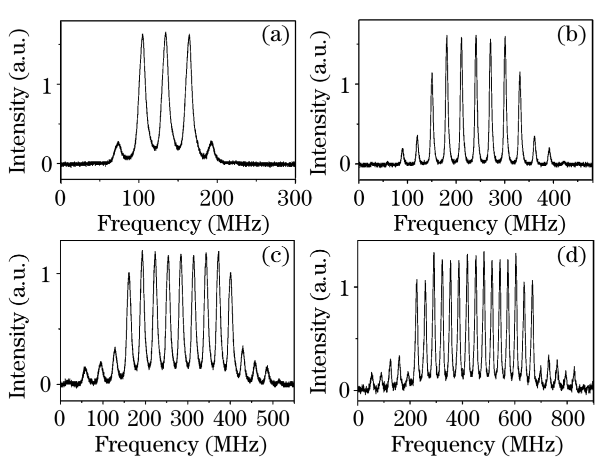

Fig. 2. Spectra of (a) three, (b) five, (c) seven, and (d) eleven equal-amplitude spectral lines.

Table 2. $\max|A_i|^2$ Values of Different Numbers of Equal-Amplitude Spectral Lines

$\max|A_3|^2$	$\max|A_5|^2$	$\max|A_7|^2$	$\max|A_{11}|^2$
0.300	0.138	0.100	0.061

amplitude moduli of fundamental frequency and the nth harmonic wave. It can also be concluded from the optimization method that spectral lines must be equal-amplitude if we want to obtain threshold as high as possible. According to the parameters of all the equal-amplitude spectral lines in Table 1, we calculated the $\max|A_i|^2$ of all the equal-amplitude spectral lines, which are presented in Table 2. In this research, the fundamental frequency of modulation signal of three, five, and seven equal-amplitude spectral lines are 60 MHz. This is because that the Brillouin bandwidth in single-mode fiber (SMF) is about 30 MHz, and the fundamental frequency needs to be twice of this frequency to separate the spectral lines well and prevent lines from interfering with each other. However, since the bandwidth of our signal generator was not large enough, the fundamental frequency of modulation signal of the eleven equal-amplitude spectral lines was set to be 40 MHz.

In the SBS suppression experiment, the beam coming out of the coupler1 was divided into two beams by a 50% coupler (coupler2). One of the two beams entered a detector D1, and the fiber-entering power was obtained. The other beam entered the SMF through an optical circulator (OC), and the power of scattering light was measured by a detector D2. The power of SBS scattering light increased gradually as the fiber-entering power increased. When the fiber-entering power reached a certain point, the SBS scattering light power increased dramatically, indicating the threshold power of SBS. We used the ratio of scattering light power P_{SBS} to the fiber-entering power P detected by D2 and D1 as the vertical axis, and P as the horizontal axis, and obtained the reflectivity curves of SBS under different modulation signals, as shown in Fig. 3.

If we define the fiber-entering power at the reflectivity of 1% as the threshold of SBS, we can obtain the experimental results of SBS threshold power for three, five, seven, and eleven equal-amplitude spectral lines. The theoretical SBS thresholds can be obtained by calculating Eq. (3) with the threshold without modulation.

The spectral lines of pump beam after being extracted by multi-frequency phase modulation split into multiple lines, which caused the broadening of the spectrum of pump beam. The energy was attributed to spectral lines according to the proportion of the square of amplitude

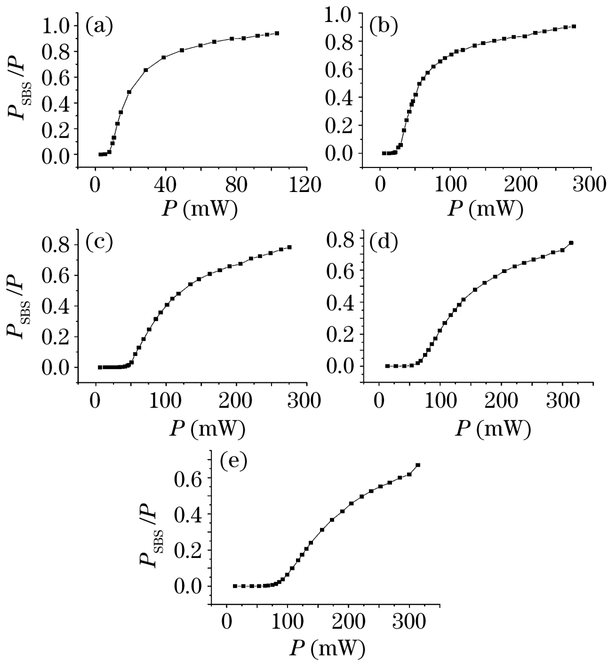

Fig. 3. Curves of reflectivity represented by P_{SBS}/P versus P under different modulation signals. (a) Non modulation, (b) three, (c) five, (d) seven, and (e) eleven equal-amplitude modulation signals.

moduli of fundamental frequency and the nth harmonic wave. This reduced the energy density of optical power spectra and increased the SBS threshold. The SBS threshold of three and five equal-amplitude spectral lines are improved by 5.21 and 8.36 dB. These consequences agree with theoretical results (5.23 and 8.60 dB) very well. But the experimentally obtained SBS threshold of seven equal-amplitude spectral lines is improved by 9.39 dB, which does not match well with the theoretical result of 9.99 dB. This is because the three and five equal-amplitude spectral lines are relatively ideal lines after modulation, while the nonuniformity caused by amplification of modulator driving voltage for the seven equal-amplitude spectral lines makes the results poor. The fundamental frequency of modulation for three, five, and seven equal-amplitude spectral lines are 60 MHz, with wide interval and clear separation among the lines, while the Brillouin bandwidth in SMF is about 30 MHz, so the interference is small. The SBS threshold of eleven equal-amplitude spectra lines is improved by 10.76 dB (12.15 dB in theory), because the interference is relatively large for the eleven equal-amplitude spectral lines due to its fundamental frequency of 40 MHz.

In conclusion, we have obtained equal-amplitude spectral lines by a new method using only one phase modulation, and applied it to suppress SBS in optical fibers. In experiment, we have obtained three, five, seven, and eleven equal-amplitude spectral lines, with flatnesses less than 0.3 dB. The experimental results show that the SBS thresholds are increased by 5.21, 8.36, 9.39, and 10.76 dB for three, five, seven, and eleven equal-amplitude spectral lines, respectively. There is a notable improvement for the SBS threshold power under the equal-amplitude condition, and it matches well with theoretical calculations.

References

1. J. Yang, Z. Guo, and K. Zha, Chinese J. Lasers (in Chinese) **28,** 439 (2001).
2. J. Yang, K. Zha, and T. Tu, Acta Photon. Sin. (in Chinese) **29,** 53 (2000).
3. F. W. Willems, W. Muys, and J. S. Leong, IEEE Photon. Technol. Lett. **6,** 1476 (1994).
4. C. Li, Opt. Optoelectron. Technol. (in Chinese) **3,** 9 (2005).
5. C. Li, J. He, and J. Xu, Study Opt. Commun. (in Chinese) (1) 3 (2005).
6. S. K. Korotky, "Multifrequency lightwave source using phase modulation for suppressing stimulated Brillouin scattering in optical fibers" US Patent 5,566,381 (Oct. 15, 1996).
7. Z. Lu, Y. Dong, and Q. Li, Opt. Express **15,** 1871 (2007).
8. Y. Dong, Z. Lu, and Q. Li, J. Opt. Soc. Am. B **25,** C109 (2008).