Enhancing stimulated Brillouin scattering in the waveguide grating*

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We obtain the enhanced stimulated Brillouin scattering (SBS) by adding the optimized Bragg grating to an As_2S_3 chalcogenide half suspended-core rectangle waveguide. The half suspended-core waveguide grating is characterized by the period of 344.67 nm and the refractive index modulation depth of 0.000 1. Through simulation experiments, the obtained Brillouin gain is 58.5 dB and the 3 dB bandwidth can reduce to 7.8 MHz. The half suspended-core waveguide structure can decrease the size of the chip while the periodic structure can enhance the slow light effect, so we have improved the integration of the waveguide and enhanced SBS by combining these two advantages.

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Photonic structures that have periodic variation of refractive index are called photonic crystals (PCs) or photonic gratings[1]. The periodic variation gives rise to a photonic band gap (PBG) in the wavelength range from visible to near infrared (IR) region when the period is several hundred nanometers. On the edge of the band gap in the periodic structure, narrow peaks of high transmission exist at frequencies where light interferes constructively in the forward direction. In the vicinity of these transmission peaks, light reflects back and forth numerous times across the periodic structure and experiences a large group delay[2]. From a macro perspective, the light-matter interaction will be enhanced as this group delay increases the interaction length or interaction time in the waveguide. Nonlinear interactions, such as stimulated Brillouin scattering (SBS), usually appear when light power is strong enough or waveguide length is long enough, which will reduce energy utilization and waveguide integration. Due to slow-light propagation, the combination of strong field enhancement with prolonged light-matter interaction is a powerful technique for overcoming material constraints and can lead to a significant reduction in the size of photonic structures[3-5]. Based on this idea, several milestone demonstrations[6,7] in photonic circuits have been reported, including slow-light enhanced third-harmonic generation[8], four-wave mixing[9], slow-travelling solitons[10] and gain enhancement in lasers[11]. SBS, one of the strongest nonlinear interaction, has been demonstrated in theory. It can be dramatically enhanced at the Brillouin zone boundary where the decreased group velocity of light magnifies photon-phonon interaction[12]. This discovery provides a possibility to strengthen the SBS from an improved waveguide structure. Recently, band-edge effects on SBS have been experimentally demonstrated using Bragg grating[13]. Based on the As_2S_3 platform, chalcogenide photonic integrated circuits are designed, wavelength-scale waveguides are enabling novel on-chip functionalities, and integrated microwave photonic signal processing has attracted increasing research for applications[14-16]. The As_2S_3 ridge waveguide has previously exhibited a gain of up to 52 dB by using SBS effect in 23 cm propagation length. It is necessary to reduce the length of the waveguide for integration[17]. The single microring waveguide has realized high gain SBS effect. Though the size has been smaller, there are strict requirements for the fabrication[18].

In this paper, we combine the As_2S_3 chalcogenide half suspended-core rectangle waveguide with Bragg grating. The half suspended-core waveguide structure can increase waveguide integration while Bragg grating can enhance SBS by using the slow light effect. When we add the Bragg grating to an As_2S_3 chalcogenide half suspended-core rectangle waveguide, and then we adjust the period of the Bragg grating to make the Stokes wave fall into the slow-light region at the band edge of the PBG. Meanwhile, to make the slow light effect more distinct, the optimum refractive index modulation coefficient is

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obtained through simulation experiments. The final waveguide grating is with the aid of an effective length of 3.9 cm, a cross-section of 0.9 μm×0.9 μm, the grating period of 344.67 nm and the refractive index modulation depth of 10^{-4}. Through simulation experiments, the final Brillouin gain obtained is 58.5 dB and the 3 dB bandwidth can reduce to 7.8 MHz. Fig.1 shows the basic structure of the grating waveguide. The half suspended-core structure stays the same as the initial version. The refractive index of core As_2S_3 changes periodically along the direction of light propagation according to the law of sines, which can be seen as the waveguide Bragg grating structure.

Ideally, in the normal waveguide, the propagation mode and the radiation mode satisfy the orthogonality relation. But in the non-ideal situation, the waveguide structure is more or less incomplete, such as waveguide loss, waveguide boundary or geometric distortion, material inhomogeneity, which will result in the energy exchange between the waveguide modes, and we call it mode coupling.

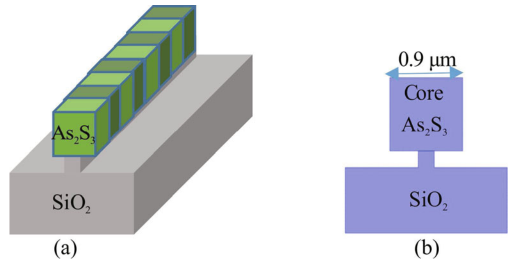


Fig.1 (a) Structure of the waveguide grating; (b) Cross section of the waveguide grating

The Bragg grating is characterized by the change of the refractive index along the direction of propagation, so we can analysis the Bragg grating by mode coupling theory. μ and ν are any two modes in the waveguide, and the propagation constants are β_μ and β_ν, respectively. The modal coupling equation can be expressed as

$$\begin{cases} \dfrac{\mathrm{d}b_\mu}{\mathrm{d}z} + \mathrm{i}\beta_\mu a_\mu = \sum\limits_\nu K^{(1)}_{\mu\nu} a_\nu \\ \dfrac{\mathrm{d}a_\mu}{\mathrm{d}z} + \mathrm{i}\beta_\mu b_\mu = \sum\limits_\nu K^{(2)}_{\mu\nu} b_\nu \end{cases}, \tag{1}$$

where $K^{(1)}_{\mu\nu}$ and $K^{(2)}_{\mu\nu}$ are modal coupling coefficients, a_x and b_x are the electric field modulus and the magnetic field modulus, respectively. The summation term on the right side of the equation represents the interaction between the modes. The coupling strength is determined by the modal coupling coefficient. Because the refractive index modulation depth of the Bragg grating is very small, we can think that the perturbation results in the coupling. According to the bidirectional mode coupling method and Eq.(1), bidirectional mode coupling equation can be given by

$$\begin{cases} \dfrac{\mathrm{d}}{\mathrm{d}z} c_\mu^+ = \sum\limits_\nu \left[K^+_{\mu\nu} c_\nu^+ \mathrm{e}^{\mathrm{i}(\beta_\mu-\beta_\nu)z} + K^-_{\mu\nu} c_\nu^- \mathrm{e}^{\mathrm{i}(\beta_\mu+\beta_\nu)z} \right] \\ \dfrac{\mathrm{d}}{\mathrm{d}z} c_\mu^- = -\sum\limits_\nu \left[K^-_{\mu\nu} c_\nu^+ \mathrm{e}^{-\mathrm{i}(\beta_\mu+\beta_\nu)z} + K^+_{\mu\nu} c_\nu^- \mathrm{e}^{-\mathrm{i}(\beta_\mu-\beta_\nu)z} \right] \end{cases}, \tag{2}$$

where c is the mode amplitude, and + and – represent forward direction and backward direction, respectively. In general, there is single mode transmission in the micro-nano waveguide, so we can get Eq.(3) from Eq.(2) as

$$\begin{cases} \dfrac{\mathrm{d}}{\mathrm{d}z} c^+ = K^+ c^+ + K^- c^- \mathrm{e}^{\mathrm{i}2\beta z} \\ \dfrac{\mathrm{d}}{\mathrm{d}z} c^- = -K^+ c^- - K^- c^+ \mathrm{e}^{-\mathrm{i}2\beta z} \end{cases}. \tag{3}$$

The refractive index distribution of the Bragg grating can be expressed as

$$n = n_0 + \Delta n \cos(\Omega z). \tag{4}$$

The relationship between Bragg wavelength and grating period can be written by

$$\lambda_B = 2\Lambda n_{eff}, \tag{5}$$

where n_0 is the refractive index of the core, Δn is the refractive index modulation depth, Ω is the grating space frequency, $\Omega=2\pi/\Lambda$, and Λ is grating period. The solution of Eq.(3) can be expressed as

$$\begin{cases} c^+ = c_0 \dfrac{\alpha \mathrm{ch}\left[\alpha(z-L)\right] - \mathrm{i}q\mathrm{sh}\left[\alpha(z-L)\right]}{\alpha \mathrm{ch}(\alpha L) + \mathrm{i}q\mathrm{sh}(\alpha L)} \mathrm{e}^{\mathrm{i}qz} \\ c^- = c_0 \dfrac{\mathrm{i}(\tilde{K}/2)\mathrm{sh}\left[\alpha(z-L)\right]}{\alpha \mathrm{ch}(\alpha L) + \mathrm{i}q\mathrm{sh}(\alpha L)} \mathrm{e}^{-\mathrm{i}qz} \end{cases}, \tag{6}$$

where q is detuning index expressed as $q=\beta-\Omega/2$, $\tilde{K} = K_0\Delta n$, where K_0 is wave vector in vacuum, and $\alpha^2 = \tilde{K}^2/4 - q^2$. According to Eq.(5), the reflectivity of the grating can be expressed as

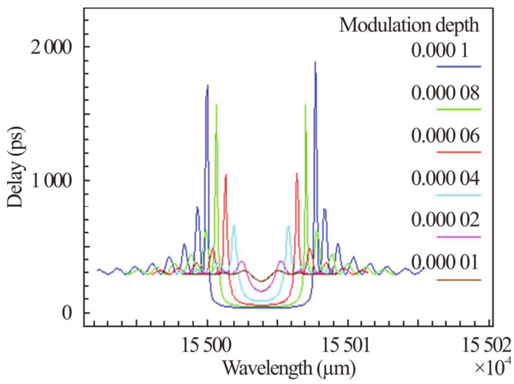
$$R = \rho^2 = \frac{(\tilde{K}^2/4)\sin^2(\alpha' L)}{\alpha'^2 + (\tilde{K}^2/4)\sin^2(\alpha' L)}, \tag{7}$$

where ρ is the reflection coefficient and $\alpha=\mathrm{i}\alpha'$. Because the grating has the characteristic of wavelength selectivity, the delays are different for the light at different wavelengths. According to the phase of the reflection coefficient ρ, the group delay can be expressed as

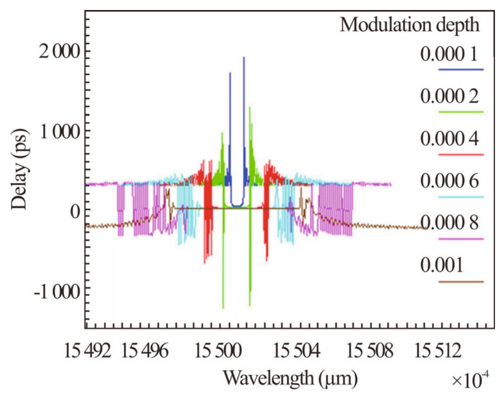
$$\tau_p = \frac{\mathrm{d}\theta_p}{\mathrm{d}\omega} = -\frac{\lambda^2}{2\pi c}\frac{\mathrm{d}\theta_p}{\mathrm{d}\lambda}, \tag{8}$$

where θ_p is the phase of the reflection coefficient. From the macro view, light-matter interaction will be enhanced because this group delay increases interaction length or interaction time in the waveguide. In this paper, we enhance the SBS using the Bragg grating because there is a huge delay on the edge of the band gap in the Bragg grating.

In general, the Bragg grating gives rise to a PBG near the Bragg wavelength. Near the band edges, light signals propagate at a slower rate due to multiple coherent reflections, which leads to a stronger light field. The sudden change of refractive index will form the structure of a reflection cavity at the edge of the reflection band, which expands the transmission time of light with a specific frequency. As shown in Fig.2, the delay in the waveguide is due to the strengthening or prolongation of the interaction between light and matter. The mode characteristic equation of three-dimensional waveguide is derived, and the smaller waveguide size can be obtained. The most fundamental principle is that we choose the largest group delay on the premise that the pump wave can transmit very well in the waveguide Bragg grating. Because the waveguide materials and dimensions stay the same as the half suspended-core structure, we adjust the grating period and the refractive index modulation depth to make sure that we can get the largest group delay at the Stokes wavelength. As a general rule, the gap position is determined by the grating period while the group delay is determined by the refractive index modulation depth. An appropriate grating period is set to make sure that the band gap is close to 1 550 nm, a general communication wavelength. For Bragg grating, the value of the modulation depth generally ranges from 10^{-5} to 10^{-3}. According to Eq.(8), we can obtain the group delay as Fig.2.



(a)

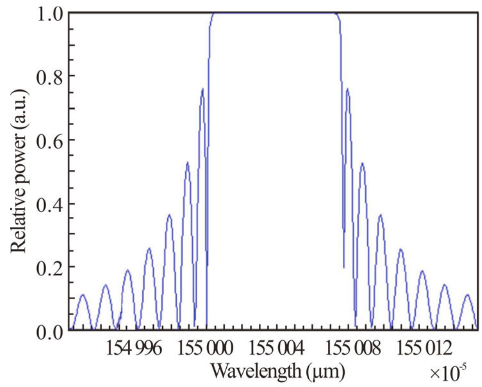


(b)

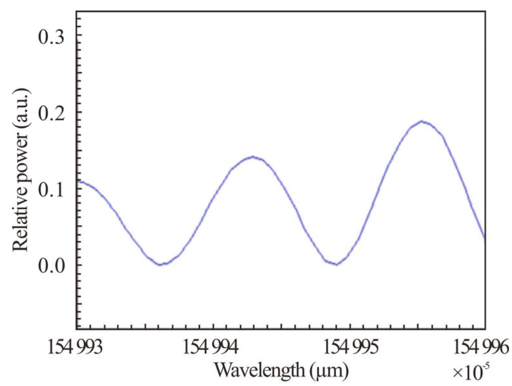
Fig.2 Delay versus wavelength for modulation depth ranging (a) from 10^{-5} to 10^{-4} and (b) from 10^{-4} to 10^{-3}

It can be seen from the Fig.2 that there is the largest group delay when the refractive index modulation depth is 10^{-4}, and the peak of the group delay is located at the band edges. For a homogeneous Bragg grating, it has a strong coupling effect for the light satisfying Bragg wavelength, but the coupling of light outside the PBG is relatively small.

The abrupt boundaries of the raster form a structure similar to Fabry-Perot cavity, and the zero point in the reflection spectrum resembles the resonant peak of the Fabry-Perot cavity. So the light at the edge of the band gap travels back and forth within the grating and therefore has a larger group delay. It's shown that 10^{-4} is the most appropriate modulation depth for our waveguide grating. Since we need to ensure that pump light is transmitted normally within the waveguide, the grating reflection spectrum is shown in Fig.3.



(a)



(b)

Fig.3 (a) The grating spectral response; (b) Regional enlarged view for (a)

According to Fig.3, the grating has a band gap width of about 10 GHz while the Brillouin frequency shift is 7.9 GHz. Because the wavelength of the pump light is less than the Stokes wavelength, if we make Stokes wave fall on the right band gap edge, the pump wave will fall into the PBG and cannot be normally transmitted.

Therefore, according to Eq.(5) and Eq.(8), we can obtain the group delay of the left band gap edge as Fig.4.

We can see that the wavelength corresponding to the largest group delay is 1 550 nm, which is the wavelength of Stokes wave, and the grating period is 344.67 nm according to Eq.(5). Because the wavelength of Stokes wave is 1 550 nm, we can obtain the wavelength of pump light ~1 549.938 nm based on Brillouin shift. From

Fig.3 we can see that the reflectivity of the pump light is 0.05, which almost does not affect the normal transmission of pump wave. So it is appropriate for our work when the refractive index modulation depth is 10^{-4} and the grating period is 344.67 nm. The group delay and dispersion are shown in Fig.5(a) when the refractive index modulation depth is 10^{-4}. As a comparison, the group delay and dispersion are shown in Fig.5(b) when there is no Bragg grating. The enhancement of the nonlinear interactions at the band edge of the PBG can be attributed to an amplified light-matter interaction in the slow-light regime by a factor $S=\tau_a/\tau_b$. This slow-down factor S determines how much slower a light signal travels in the PBG structure compared with the bare waveguide.

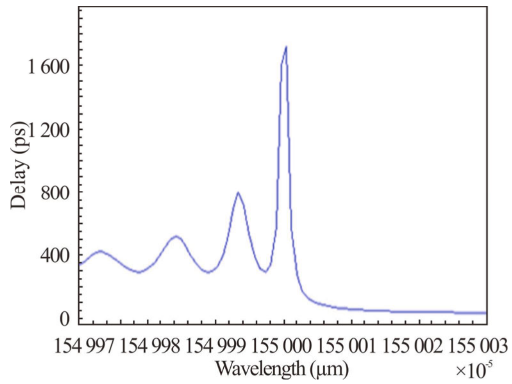


Fig.4 Group delay of the left band gap

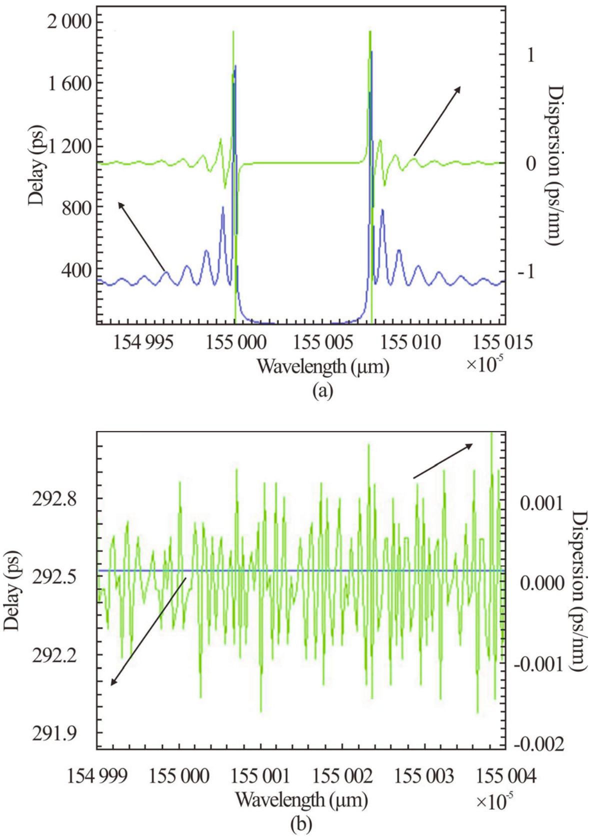


Fig.5 Group delay and dispersion versus wavelength (a) when the refractive index modulation depth is 10^{-4} and (b) when there is no Bragg grating

According to Fig.5, at 1 550 nm, τ_a=1 700 ps and τ_b=292 ps, so S=5.8. The SBS gain G increases exponentially with the Brillouin gain coefficient g_0 and the input pump power $P_{\rm pump}$[19]. In a similar approach as used to describe the gain enhancement of band-edge lasers, G is expected to increase in the slow-light region due to a build-up of the local energy density proportional to S[20]. The energy build-up is a result of the coherent coupling of forward-travelling and backward-travelling waves through the grating. According to the SBS theory, when the As_2S_3 chalcogenide half suspended-core rectangle waveguide with Bragg grating is combined, the SBS gain G and 3 dB bandwidth are shown in Fig.6 and Fig.7, respectively.

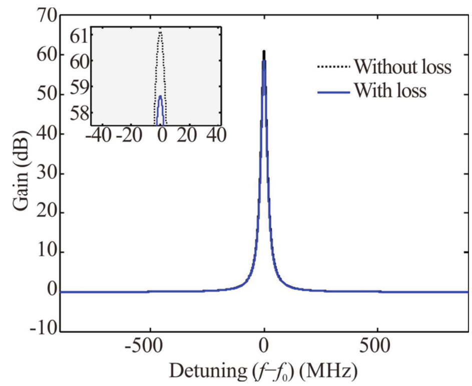


Fig.6 Gain characteristics of SBS

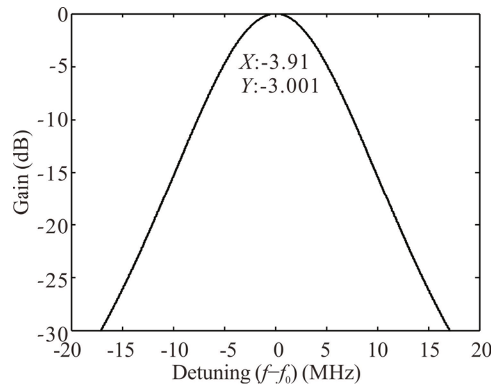


Fig.7 3 dB bandwidth of the SBS

From the perspective of practical application, this study selects the minimum waveguide size and maximizes the SBS gain as much as possible, and finally determines the semi-suspended waveguide structure based on As_2S_3 platform. The optimal size is verified by theoretical calculation and simulation experiment of the structural model. According to Fig.6, an enormous gain of 61 dB and tiny 3 dB bandwidth of 7.8 MHz are achieved in the ideal situation. Taking the practical application into account, waveguide loss is unavoidable. In addition to the theoretical waveguide loss of 0.25 dB/cm in the bare waveguide, the reflection loss of grating is also very important. Fig.3 indicates that the reflectivity of the pump light is 0.05, which means that the effective pump power is only 235 mW. According to the SBS theory, we can finally obtain the gain of 58.5 dB as Fig.6, which has some improvement compared to the gain of 54 dB obtained by using the bare waveguide. Meanwhile, the linewidth is narrower than the former work, which means that the selectivity of SBS is further enhanced.

We obtain the enhanced SBS with gain of ~58.5 dB and 3 dB bandwidth of ~7.8 MHz by adding the optimized Bragg grating to an As_2S_3 chalcogenide half suspended-core rectangle waveguide. Firstly, we use a series of theoretical analysis and simulation experiments to determine the most appropriate refractive index modulation depth of $\sim 10^{-4}$ in order to achieve the maximum slow light effect. Then, the SBS features and the Bragg grating properties are combined to make Stokes light fall on the left band gap edge, and the corresponding grating period is 344.67 nm. Finally, based on the slow-light factor, the gain and linewidth characteristics of SBS are obtained and their losses are analyzed briefly. Both Bragg gratings and the As_2S_3 chalcogenide half suspended-core rectangle waveguide can enhance SBS, and our biggest breakthrough is the combination of these two structures and we give the optimal structural parameters. In fact, any kind of nonlinear effect that requires high pump power can reduce its threshold power using slow light. The introduction of the slow light effect is also a good choice for those Si-based materials which have good compatibility with CMOS but low nonlinearity.

Statements and Declarations

The authors declare that there are no conflicts of interest related to this article.

References

[1] KURODA K, SAWADA T, KURODA T, et al. Enhanced spontaneous emission observed at one-dimensional photonic band edges[J]. Journal of the optical society of America B, 2009, 27(1)：45-50.

[2] WEN H, TERREL M, FAN S H, et al. Sensing with slow light in fiber Bragg gratings[J]. Sensors journal, IEEE, 2012, 12(1)：156-163.

[3] KRAUSS T F. Why do we need slow light?[J]. Nature photonics, 2008, 2：448-450.

[4] FIGOTIN A, VITEBSKIY I. Slow light in photonic crystals[J]. Waves in random and complex media, 2006, 16(3)：293-382.

[5] THÉVENAZ L. Slow and fast light in optical fibres[J]. Nature photonics, 2008, 2：474-481.

[6] VLASOV Y A, O'BOYLE M, HAMANN H F, et al. Active control of slow light on a chip with photonic crystal waveguides[J]. Nature, 2005, 438(7064)：65-69.

[7] SOLJAČIĆ M, JOANNOPOULOS J D. Enhancement of nonlinear effects using photonic crystals[J]. Nature materials, 2004, 3(4)：211-219.

[8] CORCORAN B, MONAT C, GRILLET C, et al. Green light emission in silicon through slow-light enhanced third-harmonic generation in photonic-crystal waveguides[J]. Nature photonics, 2009, 3：206-210.

[9] MONAT C, EBNALI-HEIDARI M, GRILLET C, et al. Four-wave mixing in slow light engineered silicon photonic crystal waveguides[J]. Optics express, 2010, 18(22)：22915-22927.

[10] MOK J T, STERKE C D, LITTLER I, et al. Dispersionless slow light using gap solitons[J]. Nature physics, 2006, 2(11)：775-780.

[11] DOWLING J P, SCALORA M, BLOEMER M J, et al. The photonic band edge laser：a new approach to gain enhancement[J]. Journal of applied physics, 1994, 75(4)：1896-1899.

[12] QIU W, RAKICH P T, SOLJACIC M, et al. Stimulated Brillouin scattering in slow light waveguides[EB/OL]. (2012-10-02)[2021-12-08]. http：//export.arxiv.org/abs/1210.0738.

[13] MERKLEIN M, KABAKOVA I V, BÜTTNER T F S, et al. Enhancing and inhibiting stimulated Brillouin scattering in photonic integrated circuits[J]. Nature communications, 2015, 6：6396.

[14] ZARIFI A, STILLER B, MERKLEIN M, et al. On-chip correlation-based Brillouin sensing：design, experiment, and simulation[J]. Journal of the optical society of America B, 2019, 36(1)：146.

[15] SHEN W, ZENG P, YANG Z, et al. Chalcogenide glass photonic integration for improved 2μm optical interconnection[J]. Photonics research, 2020, 8(9)：7.

[16] WANG K, CHENG M, SHI H, et al. Demonstration of stimulated Brillouin scattering in a silicon suspended microring with photonic-phononic waveguide[J]. Journal of lightwave technology, 2022, 40(1)：121-127.

[17] CHOUDHARY A, MORRISON B, ARYANFAR I, et al. Advanced integrated microwave signal processing with giant on-chip Brillouin gain[J]. Journal of lightwave technology, 2017, 35(4)：846-854.

[18] MIRNAZIRY S R, WOLFF C, STEEL M J, et al. Stimulated Brillouin scattering in silicon/chalcogenide slot waveguides[J]. Optics express, 2016, 24(5)：4786-4800.

[19] BOYD R W. Nonlinear optics[M]. 3rd ed. Salt Lake City ：Academic Press, 2020.

[20] JACOB B K. Slow light in various media：a tutorial[J]. Advances in optics and photonics, 2010, 2(3)：287-318.