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# Limits of broadband fiber optic parametric devices due to stimulated Brillouin scattering

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ABSTRACT

We experimentally find a practical stimulated Brillouin scattering (SBS) threshold for broadband high-performance fiber optical parametric devices relying on dispersion-stable $GeO_2$-doped silica highly nonlinear fibers. We demonstrate that SBS limits the nonlinear phase shift in such fibers to ~0.3 rad per pump unless the SBS is mitigated in some way. We consequently derive corresponding limits on signal gain and conversion efficiency and find the required SBS mitigation factor for a range of fiber optic parametric devices' applications. Finally, we examine the level of SBS mitigation using air gaps and fiber tapers for implementation in polarization-insensitive fiber optic parametric devices employing bidirectional loops. We observe that an air gap or fiber taper are not very efficient for SBS mitigation as they provided an increase in SBS threshold up to 0.7 dB attributed primarily to their excess loss.

## 1. Introduction

Fiber optic parametric devices (FOPD) have received much attention due to their wavelength unrestricted [1] abilities for broadband [2] and phase-sensitive [3] amplification, optical phase conjugation [4], wavelength conversion [5] and phase regeneration [6]. FOPD rely on the third-order nonlinear response of an optical fiber invoked by high power pump(s).

Stimulated Brillouin scattering (SBS) limits the pump power employable by a parametric device and thus restricts its performance. The SBS backscatters an exponentially increasing fraction of pump power until the pump is depleted. A significant pump depletion due to the SBS occurs at a critical power $P_{cr}$ defined by (1) [7], where $g_B$ is the peak Brillouin gain, $L_{eff}$ is the effective fiber length, $A_{eff}$ is the fiber effective area, $K$ is the pump polarization factor between 1 and 2, $\Delta\nu_B$ is the Brillouin bandwidth and $\Delta\nu_P$ is the pump linewidth.

However, the SBS deteriorates the pump before any depletion occurs. Back reflections and Rayleigh backscattering can provide external feedback for the SBS resulting in pump power oscillations [8,9]. Additionally, the SBS can increase pump intensity noise significantly [10,11]. Therefore, we use a practical definition of the SBS threshold as the input pump power when 1% of incoming pump is backscattered. Exceeding this threshold typically leads to a notable pump degradation.

$$P_{cr} \approx 21 \times \frac{A_{eff}K}{g_B L_{eff}} \times \frac{\Delta\nu_P \otimes \Delta\nu_B}{\Delta\nu_B} \quad (1)$$

One common way to mitigate SBS relies on pump linewidth $\Delta\nu_P$ increase, most often via pump phase modulation known as dithering [12,13]. Pump dithering is often used in fiber optic parametric amplifiers, but it leads to degradation of the amplified signals [14–17]. Thus, pump dithering is avoided in phase-sensitive amplifiers [18], because it can offset any gains of phase-sensitive amplification. The implementation of pump dithering for wavelength conversion or phase conjugation is avoided or very restricted, because it is even more detrimental for idlers than for signals [20] even when using techniques with reduced impact on idlers, i.e. counter-phase dithering of two pumps [19] or binary phase modulation [13].

Another way to mitigate the SBS is by reducing the Brillouin peak gain $g_B$. This can be done by a longitudinal variation of the SBS Stokes shift along an optical fiber via fiber strain distribution [21], nonuniform dopant concentration [22], temperature distribution [23] or core radius variation [24]. The problem with this approach is a significant longitudinal dispersion variation associated with the induced fiber nonuniformity. Thus, SBS mitigation by a factor of ~4 resulted in a 30 nm

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variation in zero dispersion wavelength in [25,26]. Such a significant dispersion variation is not suitable for broadband FOPDs requiring the zero dispersion wavelength fluctuation to be within ~0.1 nm wide range [27]. SBS mitigation can be achieved with less dispersion fluctuation by decreasing an overlap between acoustic and optical modes [28], pre-compensating of the strain-induced dispersion variation [29] or employment of Al-doped fibers [26]. However, these approaches has not so far been demonstrated with truly dispersion stable highly nonlinear fibers (HNLF) required for broadband FOPD operation [2].

Broadband low-penalty FOPDs require narrow-linewidth pumps and state-of-the-art dispersion-stable HNLFs, therefore alternative SBS mitigation techniques are needed. One of them is splitting a gain fiber into *N* stages with optical isolators to increase the SBS threshold by a factor up to *N* [30]. This approach allowed for a multiple-stage dithering-free fiber optic parametric amplifier [25]. However, optical isolators are not compatible with state-of-the-art polarization-insensitive FOPD relying on bidirectional signal propagation in a polarization-diversity loop [3,5,31–33]. Bidirectional air gaps are proposed in [34] to replace optical isolators and to mitigate the SBS through interruption of acoustic wave propagation, but this has not previously been demonstrated to the best of our knowledge. Additionally, fiber tapers have been used for SBS mitigation [35], so they have a potential to replace optical isolators in bidirectional loops with little impact on the FOPD performance, whilst attenuating an acoustic wave [36].

In this paper we experimentally study the SBS-induced limitations in broadband high-performance FOPD employing dispersion-stable HNLF. We measure a practical SBS threshold for a range of lengths of two different dispersion-stable HNLFs and demonstrate the SBS to limit the nonlinear phase shift in dispersion-stable $GeO_2$-doped silica HNLFs to ~0.3 rad per pump unless the SBS is mitigated in some way. We consequently derive corresponding limits on signal gain and conversion efficiency and evaluate the required SBS mitigation factor for most common applications of FOPD. Finally, we examine SBS mitigation using air gaps and fiber tapers, with neither the gain fiber nor the pump quality being compromised. These developments are compatible with polarization-diversity loops employed in state-of-art FOPD.

## 2. Experimental setup

Fig. 1 shows the experimental setup for the SBS characterization. A pump was sourced from a 100 kHz linewidth laser, passed through a polarization scrambler to avoid polarization dependent variations of Brillouin gain [7] and then amplified in an EDFA with maximum output power of 2 W. A circulator was used to couple the pump into the tested fiber and to guide the power backscattered from the fiber into a power meter PM3. Power meters PM1 and PM2 measured power at the fiber input and output via calibrated tap couplers.

The SBS was characterized by varying the input pump power and measuring the backscattered and the output pump powers. Attenuation of each SMF-to-HNLF splice was estimated and accounted to find the powers at the ends of tested fibres. Then, the backscattered-to-input pump power ratio was derived and used to find the SBS threshold reached at the ratio of –20 dB.

First, the SBS threshold was analyzed as a function of the nonlinear phase shift for a range of lengths of two dispersion-stable $GeO_2$-doped silica HNLFs typically employed in FOPD (Fig. 2(a)). The nonlinear phase shift was calculated as a product of the input pump power, the fiber length and the fiber nonlinearity. Fiber A was a non-commercial dispersion-stable HNLF [37]. Fiber B was a dispersion-stable HNLF commercially sourced from OFS. Both fibers had attenuation of ~1 dB/km. Their nonlinearities of ~14 $W^{-1}km^{-1}$ and ~8 $W^{-1}km^{-1}$ respectively were provided in datasheets and additionally verified based on the maximum peak gain in [2,32].

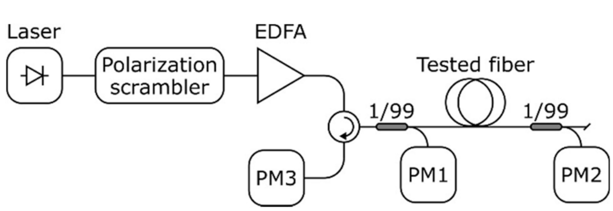


**Fig. 1.** Experimental setup for SBS characterization in HNLF and comparison of SBS mitigation techniques.

Second, the impact of a range of passive components on the SBS threshold was characterized (Fig. 2(b)). The SBS threshold was measured for two 25 m lengths of fiber A connected via an optical isolator, a fiber taper, an air gap or a bend loss. The optical isolator provided an isolation of ~35 dB and return loss > 50 dB. The fiber taper was adiabatic with a neck of ~1.5 µm and length of ~38 mm. The air gap was a pair of collimators provided by a free-space variable optical attenuator set to minimal attenuation. All investigated mitigation techniques introduced excess loss, so an impact of attenuation alone on the SBS threshold have been assessed by employing bend loss for SBS mitigation. The bend loss was invoked by making four fiber loops around a 21 mm diameter rod. Although fiber wound around a rod could get some strain affecting its Brillouin frequency shift, the affected fiber length was less than 1% of the examined fibers length, so its impact can be neglected.

## 3. Results and discussion

### 3.1. SBS-limited nonlinear phase shift

A nonlinear phase shift Φ of a FOPD is an important parameter defining the maximum phase-insensitive gain $G_{PIA}$, phase-sensitive gain $G_{PSA}$ and conversion efficiency $G_{idler}$ as shown in (2) [3]. Fig. 3 shows a backscattered-to-pump power ratio against nonlinear phase shift for all characterized fibers.

$$G_{PIA}^{max} = \cosh^2 \Phi; \quad G_{idler}^{max} = \sinh^2 \Phi; \quad G_{PSA}^{max} = (\cosh \Phi + \sinh \Phi)^2; \tag{2}$$

The SBS threshold is achieved in fiber A at nonlinear phase shift of 0.28 rad and in fiber B at nonlinear phase shifts of 0.27 – 0.32 rad. Fiber B shows a larger variation of the threshold nonlinear phase shift due to the fiber lengths being from different batches and hence possessing a small variation in nonlinearity and splice loss. Nevertheless, we can confirm that two dispersion-stable HNLF with very different nonlinearities (8 and 14 $W^{-1}km^{-1}$) are limited by the SBS to the same value of nonlinear phase shift per pump: $\Phi_{th} = 0.3 \pm 0.03$ rad. This agrees well with the analytical analysis below.

The maximum nonlinear phase shift $\Phi_{th}$ is provided in (3), where the

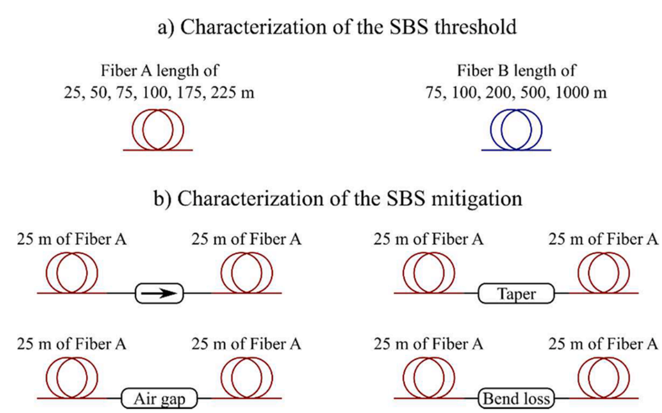


**Fig. 2.** Fibers tested for characterization of the SBS threshold a) in varied type and length HNLF; b) when an isolator, a taper, an air gap or a bend loss are employed between two lengths of HNLF.

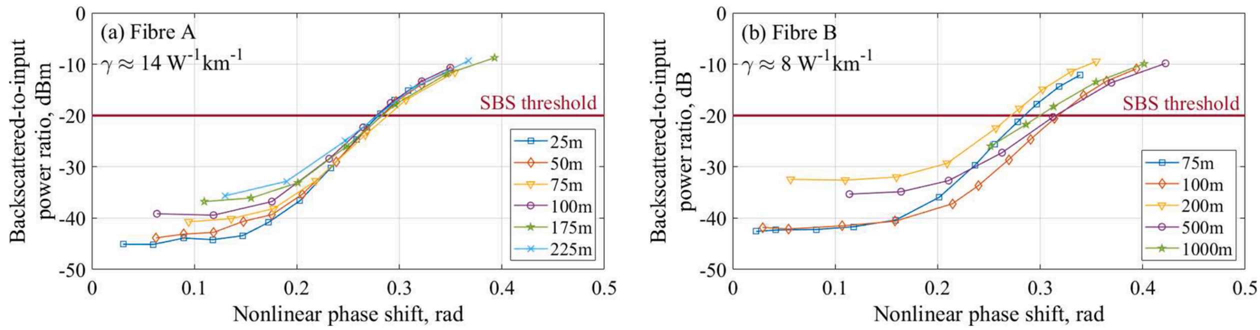


**Fig. 3.** The SBS characterization as a ratio of backscattered and input powers versus nonlinear phase shift for dispersion-stabilized HNLFs with nonlinearity γ of (a) 14 $W^{-1}km^{-1}$ and (b) 8 $W^{-1}km^{-1}$. The SBS threshold is defined as 1% of pump power being backscattered. The nonlinear phase shift is calculated as a product of pump power, fiber length and fiber nonlinearity.

fiber nonlinearity $\gamma$ is substituted with $\omega n_2/A_{eff}c$, $\omega$ is the pump frequency, $n_2$ is the nonlinear-index coefficient, and $P_{th}$ is the 1% threshold pump power. The latter is derived similarly to the critical power $P_{cr}$ in [38], whereas the backscattered power is set to be 1% of the output pump power instead of being equal to it. The resulting $P_{th}$ is defined by the same equation as (1), but with the numerical coefficient ~21 reduced by ln(100) and turned into ~16.

$$\Phi_{th} = \gamma P_{th} L_{eff} \approx \frac{\omega n_2}{c} \times 16 \frac{K}{g_B} \times \frac{\Delta\nu_P \otimes \Delta\nu_B}{\Delta\nu_B} \quad (3)$$

The key differences between the tested fibers: the effective area and the effective length, are cancelled in (3). The pump and the Brillouin bandwidth relation $(\Delta\nu_P \otimes \Delta\nu_B)/\Delta\nu_B$equals unity for narrow linewidth pumps ($\Delta\nu_P \ll \Delta\nu_B$). Therefore, the fiber properties defining the maximum nonlinear phase shift $\Phi_{th}$ are the nonlinear-index coefficient $n_2$ and the Brillouin gain coefficient $g_B$. The nonlinear-index coefficient $n_2$ is defined by the glass composition. Common HNLFs are made of silica doped by ~20–30% mol of $GeO_2$ [39,40]. However, a change of the $GeO_2$ concentration by a factor of 2.5 causes a change of $n_2$ by only ~20% [40], so $n_2$ is about the same for all common $GeO_2$-doped HNLFs. The Brillouin gain coefficient $g_B$ depends on the longitudinal fiber uniformity (variation of Brillouin frequency shift effectively decreases Brillouin gain [26]), the glass material [26] and properties of optical and acoustic modes [28,38]. Our result and its matching with other papers observing a similar maximum nonlinear phase shift $\Phi_{th}$ at the wavelength around 1550 nm (0.29 rad in [40], 0.21 rad in [26], 0.27 rad in [25]) demonstrate that Brillouin gain $g_B$ is indeed about the same for all standard HNLFs produced by various vendors and is about 13 $m \cdot W^{-1}$ based on [40]. Therefore, the SBS-limited nonlinear phase shift is in the range 0.2…0.3 rad for a range of highly nonlinear fibers, and 0.3 rad is the maximum observed for dispersion-stable HNLF.

The derived nonlinear phase shift limit of 0.3 rad per pump establishes a reference point for SBS mitigation requirements. Table 1 shows the maximum SBS-limited gain and conversion efficiency calculated using (2) for an SBS mitigation level varied from no mitigation to an SBS threshold increase by a factor of 20. Note, the maximum gain and conversion efficiency can be improved if assisted, e.g. by Raman gain [41,42].

If the SBS is not mitigated in some way, the phase-insensitive and phase-sensitive gains in single-pump fiber optic parametric amplifiers are limited to 0.4 dB and 2.6 dB respectively, which is insufficient for a practical amplifier. However, a conversion efficiency of almost −10 dB can be achieved without SBS mitigation, thus allowing for a practical optical phase conjugators and wavelength converters although requiring an external optical amplifier.

**Table 1**
The SBS-limited gain and conversion efficiency of single pump fiber optic parametric devices for a varied level of the SBS mitigation.

| SBS threshold increase factor | 1 | 2 | 3 | 10 | 20 |
|---|---|---|---|---|---|
| Max nonlinear phase shift, rad | 0.3 | 0.6 | 0.9 | 3 | 6 |
| Max phase-insensitive gain, dB | 0.4 | 1.5 | 3.1 | 20.1 | 46.1 |
| Max conversion efficiency, dB | −10.3 | −3.9 | 0.2 | 20.0 | 46.1 |
| Max phase-sensitive gain, dB | 2.6 | 5.2 | 7.8 | 26.1 | 52.1 |

An SBS threshold increase by a factor of 3 would allow for 'lossless' wavelength conversion or a substantial phase-sensitive gain of > 7 dB. This enables multiple-stage fiber optic parametric amplifiers with net gain > 10 dB as later stages deliver phase-sensitive gain [25]. An SBS threshold increase by a factor of 10 could allow for a single stage amplifier with gain up to 20 dB, and a threshold increase by a factor of 20 enables significant gain sufficient for most other likely applications.

An employment of two pumps doubles the maximum nonlinear phase shift of a FOPD [34], because the nonlinear phase shift is a function of the total pump power employed by a FOPD. Indeed, if the frequency offset between pumps is above 100 MHz (upper boundary of the SBS interaction bandwidth for most fibers [40]), each of two pumps has the same SBS threshold as a single pump, and the total pump power can be doubled. Although the maximum phase-insensitive and phase-sensitive gains are still very low for two-pump fiber optic parametric amplifiers without the SBS mitigation: 1.5 dB and 5.2 dB respectively, the required SBS mitigation factor is halved in this case. Besides, an improved conversion efficiency of ~-4 dB can be achieved without SBS mitigation in the case of two-pump FOPDs.

Overall, the SBS limits a nonlinear phase shift in dispersion stable HNLF to ~0.3 rad per pump and a significant increase of the SBS threshold is required for most applications. Since all common SBS mitigation techniques compromise performance of FOPD in some way, we next investigate novel techniques to mitigate the SBS without major drawbacks.

### 3.2. The SBS mitigation using air gaps and fiber tapers

This section evaluates the level of SBS mitigation using an air gap or a fiber taper. An impact of an isolator and a bend loss on the SBS threshold is analyzed for a reference. Results for these four scenarios are compared with the results for 25 m and 50 m fiber lengths without SBS mitigation.

Fig. 4(a) shows the backscattered-to-pump power ratio as a function of input power and allows to find the SBS threshold for each scenario. The SBS threshold of a single length of 25 m HNLF was 29.5 dBm. An addition of another 25 m length lowered the SBS threshold by 2.8 dB as expected. Insertion of an optical isolator between these fiber lengths raised the SBS threshold to 29.3 dBm therefore enabling the injection of almost as much power in the 50 m fiber as in the 25 m fiber. An insertion of an air gap, a taper and a bend increased the SBS threshold by 0.3 dB, 0.7 dB and 0.7 dB respectively.

Fig. 4(b) shows the output pump power versus the input pump power for each scenario. It allows to measure the insertion loss at the low power end and the saturated output power at the high power end.

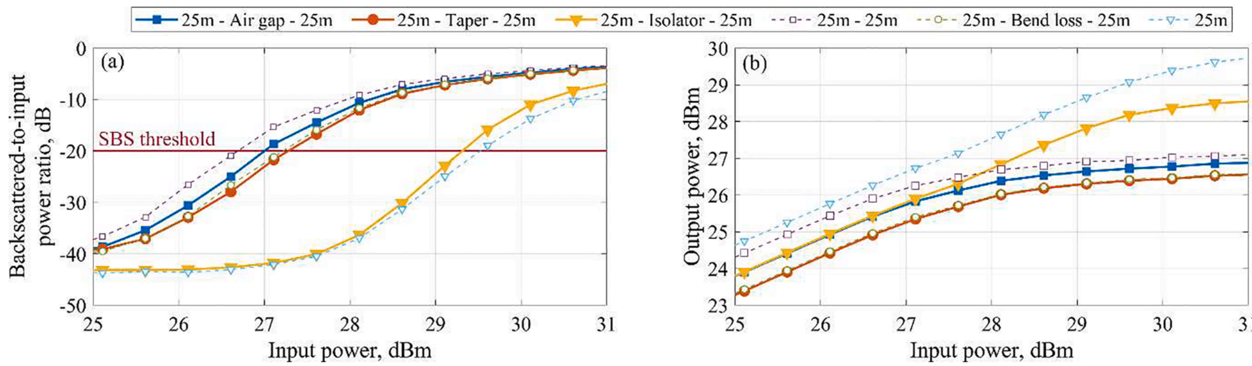


**Fig. 4.** The SBS characterization for a range of the SBS scenarios in terms of (a) backscattered-to-input pump power ratio and (b) output pump power versus input pump power. The SBS mitigation using an air gap or a fiber taper between is evaluated and compared with the SBS mitigation using an optical isolator. Following scenarios are examined for a reference: one or two concatenated 25 m fiber lengths and bend loss between the 25 m fiber lengths.

Insertion loss of the air gap and the isolator were 0.5 dB, and insertion loss of the taper and the bend were 1 dB. Therefore, only the isolator improved the SBS threshold by more than its own insertion loss and allowed for higher saturated output power than the no-mitigation scenario with the same fiber length. Additionally, the results for a fiber taper closely match the results for equivalent bend loss in both Fig. 4(a) and Fig. 4(b). It is concluded that the air gap and the fiber taper impacted the SBS mainly by their insertion loss.

We therefore could not achieve a practical SBS mitigation by employing an air gap or a fiber taper. We suggest that the reported SBS mitigation by using tapers [35] was due to changing a fiber diameter along a substantial length and was similar to SBS mitigation using varying core diameter fibers.

## 4. Conclusion

We have demonstrated the stimulated Brillouin scattering to limit the nonlinear phase shift achievable in dispersion-stable $GeO_2$-doped silica HNLFs to 0.3 rad per pump unless the SBS is mitigated in some way. Such a nonlinear phase shift allows only wavelength conversion with efficiency up to ~-4 dB if two pumps are employed. The SBS threshold must be increased at least tenfold to enable a practical fiber optic parametric amplification with a single pump. Consequently, we have examined SBS mitigation as suggested in the literature using air gaps and fiber tapers in a similar way to optical isolators. An air gap and fiber taper provided a small SBS threshold increase of less than 0.7 dB which we attributed primarily to their excess loss, so they are not very efficient for the SBS mitigation. Therefore, further work is required to enable mitigation of the SBS in net gain polarization-insensitive fiber optic parametric devices without compromising operation bandwidth and signal quality.

### CRediT authorship contribution statement

**V. Gordienko:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. **Á.D. Szabó:** Formal analysis, Investigation, Writing – original draft, Funding acquisition. **M.F.C. Stephens:** Conceptualization, Writing - review & editing, Supervision. **V. Vassiliev:** Resources. **C.B. Gaur:** Investigation. **N.J. Doran:** Conceptualization, Supervision, Funding acquisition.

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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