Alignment of zero-dispersion wavelength along highly-nonlinear fiber length with simultaneous increase in the stimulated Brillouin scattering threshold

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Abstract: We apply temperature tuning to several segments of a highly-nonlinear fiber with decreasing zero-dispersion wavelength (ZDW) to simultaneously align the segments' ZDWs and separate their stimulated Brillouin scattering (SBS) spectra, yielding higher SBS threshold.

1. Introduction

High nonlinearity and low loss of the highly-nonlinear fiber (HNLF) make it very attractive medium for optical parametric amplification (OPA, both phase-insensitive [1] and phase-sensitive [2]), optical regeneration [3, 4], wavelength conversion [5], and optical comb generation [6]. However, the maximum continuous-wave (CW) pump power in this fiber is limited by the stimulated Brillouin scattering (SBS) effect, whose mitigation requires the use of sophisticated pump phase modulation schemes [7] that often transfer the phase modulation onto the wavelength-converted (idler) beam, which is undesirable. To increase the SBS threshold in the HNLF by broadening the Brillouin gain spectrum, several approaches have been previously investigated: applying distribution of temperature [8], strain [9], or Ge concentration [10] along the HNLF length, as well as using Al doping of HNLF [11]. Unfortunately, none of these solutions are free of drawbacks: the first three approaches lead to variation of the zero-dispersion wavelength (ZDW) along the HNLF length, which reduces the OPA gain and its bandwidth [12], and the Al-doping approach increases the HNLF loss coefficient.

We propose to eliminate the ZDW-variation drawback of the temperature-tuning approach by starting with the fiber that already has a non-uniform ZDW distribution along its length, which is often the case with practical HNLFs. Then, by applying different temperatures to different segments of the fiber, one can simultaneously achieve two goals: align the ZDWs of all segments of the fiber and broaden the Brillouin gain bandwidth of the HNLF by changing Brillouin frequency shifts of individual fiber segments by different amounts. In this paper, as a proof-of-concept we employ a special ZDW-decreasing 500-m-long HNLF, where ZDW has been intentionally made non-uniformly distributed (in our case, decreasing) along the fiber length. We split it into 10 segments and, after characterization, select 4 of them, whose ZDWs can be aligned by thermal tuning within acceptable range of temperatures while broadening SBS gain spectrum at the same time. For CW pump, we demonstrate higher SBS threshold and higher achievable wavelength-conversion efficiencies in the temperature-tuned HNLF. For phase-modulated pump, we observe higher and wider OPA gain after such temperature tuning.

2. Fiber characterization and thermal-tuning experiments

Figure 1 shows the temperature tuning curves for (a) ZDWs and (b) SBS frequency shifts of the 10 individual fiber segments. ZDWs have been measured by tuning the pump wavelength and observing the transition of parametric gain from one-lobe (normal dispersion) to two-lobe (anomalous dispersion) spectrum. SBS shifts have been measured by observing beating of the backreflected pump with input pump at an RF spectrum analyzer. Figures 1a and 1b represent linear fits to data points taken from 25°C to 80°C at 5°C intervals. Based on these plots, we select and splice together 4 fiber segments (#10, #3, #7, and #5) whose ZDWs can be aligned by thermal tuning within reasonable 25°C–150°C range, while resulting in almost evenly spaced SBS gain peaks (total SBS spectrum is modeled in Fig. 2a by adding the 4 individual spectra, with inset showing experimentally measured gain spectra). The first 2 segments (#10 and #3) have largest difference in SBS gain spectra among all 4 segments. The SBS threshold, measured at backreflected power level exceeding Rayleigh background by 20 dB, exhibits 2.5 dB increase after thermal tuning. Note that such increase is only 1.6 dB when HNLF segments are arranged in reverse order, where Brillouin spectra of the first two segments #5 and #7 have small separation. This indicates that the choice of initial segments affects the SBS suppression performance in the presence of finite insertion loss (IL) of the fiber. The IL of the 4-segment 200-m-long

HNLF is 1.8 dB, which includes fiber attenuation and HNLF-HNLF splices, as well as input and output SMF-HNLF splices and connectors.

The experimental setup for characterization of the OPA performance of the spliced 4-segment HNLF under controlled thermal tuning is shown in Fig. 3. Pump light from a tunable laser source (TLS, Ando AQ4321D) goes through a polarization controller (PC) and a phase modulator (PM). By controlling an electrical switch, the BPSK modulation by 12 Gb/s 2^{11}–1 pseudorandom bit sequence (PRBS) can be turned off and on to choose either the SBS-limited (CW) mode or SBS-free (phase-modulated) mode, respectively. After the PM, the pump is amplified by two erbium-doped fiber amplifiers (EDFAs): pre-amplifier (Pre-EDFA) and high-power amplifier (HP-EDFA). Two cascaded 1-nm-wide optical bandpass filters (BPF, Koshin Kogaku) after the EDFAs block the out-of-band amplified spontaneous emission (ASE). Another TLS (Ando-8201-13B) serves as the signal and is aligned in polarization with the pump by a PC. 90% of the pump and 10% of the signal are combined with a 90/10 coupler and sent to 4-segment HNLF through a circulator that deflects the SBS-backreflected light into an optical absorber. Each fiber segment is heated by a DC heating pad controlled by PID circuit. The thermal insulation layer is wrapped outside of DC heating pad to ensure uniform temperature distribution within the fiber segment. The HNLF output, after attenuation (ATT), is observed by an optical spectrum analyzer (OSA).

The OPA performance is measured in two cases. In the first one the pump is a CW beam with narrow linewidth (200 kHz), and the OPA is limited by the SBS. We fix the input pump power at 27.1 dBm, which is well above the SBS thresholds for both room-temperature (RT, 22°C) and thermally-tuned (TT) HNLFs, so that the OPA performance is determined by the corresponding SBS threshold. Since SBS-limited pump power is small, the OPA gain is close to 1, and the best indicator of the OPA performance is the conversion efficiency (CE) to the idler wavelength. The second case is for SBS-free operation, where the pump laser is phase-modulated by a 12 Gb/s PRBS, which makes the pump linewidth 3 orders of magnitude wider than the SBS gain bandwidth, so that SBS effect becomes negligible. Using the same power of 31.8 dBm for both RT and TT operation, we observe the OPA performance (signal gain and gain bandwidth) determined by the ZDW distribution of HNLF.

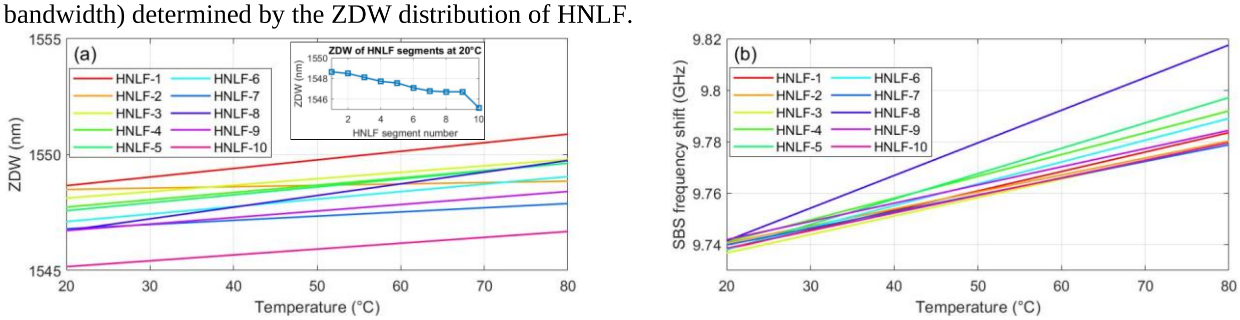

Fig. 1. (a) Linear fits to measured temperature dependence of ZDW; (b) linear fits to measured temperature dependence of SBS frequency shift.

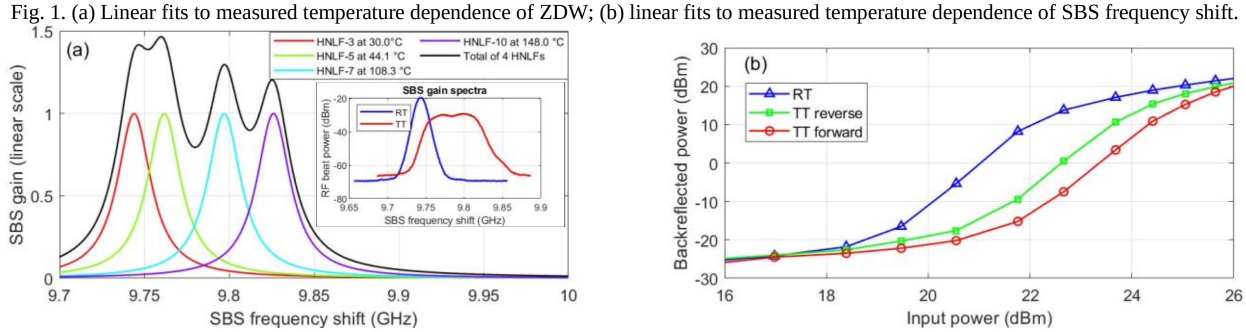

Fig. 2. (a) Predicted SBS gain spectra for optimal choice of fiber segments (#10, #3, #7, and #5) at temperatures corresponding to the same ZDW for all segments; inset – measured SBS spectra; (b) comparison of SBS backreflected power between room-temperature (RT, 22°C) and thermally-tuned (TT) regimes for forward and reverse direction in the 4-segment HNLF. For RT regime, there is no difference between the forward and reverse direction.

The OPA performance in SBS-limited case with the pump placed at ZDW (1546.2 nm for RT, 1547.5 nm for TT) is shown in Fig. 4a, demonstrating 5-dB improvement in maximum CE under TT operation. When pump is moved to (ZDW + 1 nm) position (Fig. 4b), the CE improvement becomes 5.6 dB. For SBS-free case shown in Fig. 4c for pump tuned to (ZDW + 1 nm), the maximum signal gain is improved by 2.8 dB and the OPA bandwidth with gain above 10 dB is increased by at least 25 nm for TT, compared to RT, operation.

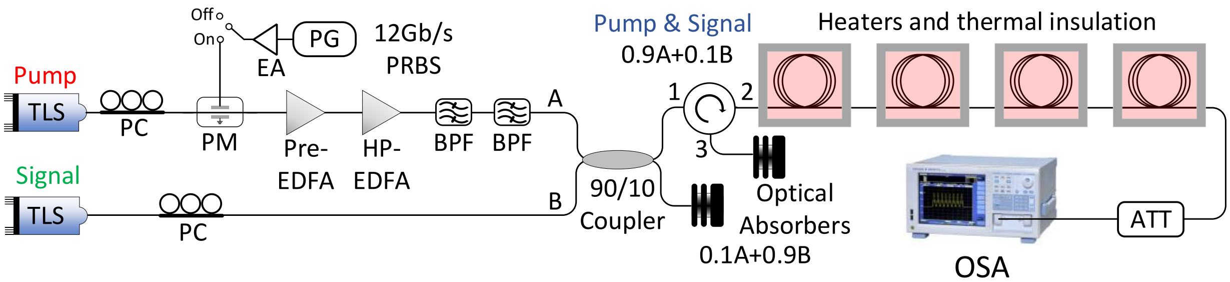

Fig. 3. Experimental setup for OPA performance characterization under thermal tuning. ATT: attenuator; EA: electrical amplifier; EDFA: Erbium doped amplifier; HP: High power; OSA: optical spectrum analyzer; PC: polarization controller; PM: phase modulator; PRBS: pseudorandom bit sequence; TLS: tunable laser source.

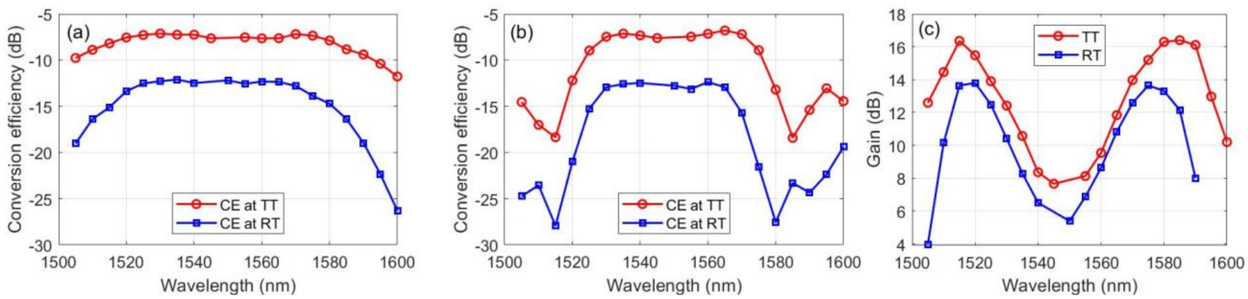

Fig. 4. Conversion efficiency (CE) for SBS-limited case with pump located at a) ZDW and b) ZDW + 1 nm. c) OPA gain spectra for SBS-free case and pump at ZDW + 1 nm.

3. Conclusion

We have shown that both SBS threshold and OPA gain of an HNLF with spatially-varying ZDW can be simultaneously improved by applying thermal tuning to various HNLF segments, which aligns their ZDWs and moves apart their Brillouin gain spectra. This opens a possibility of designing a fiber with more temperature-sensitive SBS shift, which can relax or even avoid pump phase-modulation requirements of fiber OPAs.

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5. References

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