Positive (>0 dB) Wavelength Conversion Efficiency in Temperature-Tuned Five-Segment Highly-Nonlinear Fiber Without Pump Dithering

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Abstract: By temperature tuning, we align zero-dispersion wavelengths of several fiber segments while detuning their Brillouin frequencies. Despite 2.5-fold fiber length increase, we obtain 2-dB higher Brillouin threshold, enabling >0 dB conversion efficiency without pump modulation.

1. Introduction

Large nonlinear coefficient and low loss of highly-nonlinear fibers (HNLFs) are used for both phase-insensitive [1] and phase-sensitive [2] optical parametric amplification (OPA), optical regeneration [3], wavelength conversion [4], optical comb generation [5], and many other applications. However, the stimulated Brillouin scattering (SBS) effect constrains the maximum continuous-wave (CW) pump power that can be employed in the HNLF. SBS mitigation requires the use of sophisticated pump phase dithering schemes [6] that often imprint the phase dithering onto the wavelength-converted (idler) beam, which is undesirable for coherent communications. The SBS-limited CW pump power results in low wavelength conversion efficiency (CE), which limits OPA's range of applications. The SBS threshold in the HNLF can be raised by broadening the SBS gain spectrum, for which several approaches have been investigated: applying distribution of temperature [7], strain [8], or Ge concentration [9] along the HNLF length, as well as using Al doping of HNLF [10]. Unfortunately, all of these solutions have drawbacks: the first three lead to variation of the zero-dispersion wavelength (ZDW) along the HNLF length, which reduces the OPA gain and bandwidth [11], and the Al doping increases the HNLF loss coefficient. We recently used temperature tuning in a dispersion-decreasing (DD) fiber to align ZDWs of its various segments while simultaneously detuning their SBS frequencies [12]. However, the SBS threshold increase was relatively modest, because, even after detuning, the SBS spectra of various segments still partially overlapped. In another work [13] we raised the SBS threshold while aligning ZDWs by combining a DD HNLF segment with a segment from a slightly-different (dispersion-flattened, or DF) HNLF [14]. DD-HNLF and DF-HNLF, spliced together with < 0.1 dB splice loss, had very different SBS shift frequencies, while their ZDWs could align at 40°C.

In this paper, we combine the approaches [12, 13] by employing both different HNLF types (DD and DF) and multiple temperature-detuned segments for each HNLF type. The segments with slightly different ZDWs are chosen among available samples, so that after temperature tuning their ZDWs would align while the SBS frequencies would be detuned from one another. As a result, we extend the total HNLF length from 100 m [13] to 250 m without change in the SBS threshold, which increases the CW-pumped conversion efficiency (CE) by ~10 dB over best results of [13].

2. Fiber characterization and thermal-tuning experiments

Figure 1 shows the temperature tuning curves for (a) ZDWs and (b) SBS frequency shifts for 50-m-long segments of DD-HNLF (5 segments) and DF-HNLF (6 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 with pulsed pump. SBS shifts have been acquired from the beat frequency of the backreflected and input pumps at an RF spectrum analyzer. Figures 1a and 1b represent linear fits to data points taken from 30°C to 120°C at 5°C intervals. Based on these plots, we select segments of DD-HNLF and DF-HNLF with small ZDW differences to reduce the temperature range required for ZDW alignment. 100-m-long DD-HNLF is made by splicing the segments DD-5 and DD-7, both of which have ~1547.3 nm ZDW and 9.74 GHz SBS frequency shift at room temperature (RT). 100-m-long DF-HNLF is made by splicing the segments DF-1 and DF-3, both of which have 1550.2 nm ZDW and 9.29 GHz SBS frequency shift at RT. 100-m-long customized DF-DD-HNLF is made by splicing the segment DF-4 and the segment DD-3, whose tuning curves yield equal ZDWs of 1548.7 nm and two separate SBS gain peaks (9.3 GHz for DF-4 and 9.76 GHz for DD-3) at tuned temperature 40°C (TT) [13]. 250-m-long customized DF-DD-HNLF is made by splicing 5 segments DD-1, DD-9, DF-6, DF-2, and DF-10, whose tuning curves yield equal ZDWs of 1550.9 nm and five separate SBS gain peaks at 9.79, 9.86, 9.33, 9.28, and 9.37 GHz for 81, 169, 77, 15, and 131°C (TT), respectively, as shown in SBS spectra in Fig. 2a and by red (for DF) and blue (for DD) circles in Figs. 1a,b. At RT, 250-m fiber has only two SBS peaks: 9.29 GHz (DF fiber segments) and 9.74 GHz (DD fiber segments).

With such thermal tuning (TT), the SBS threshold of 100-m-long DF-DD-HNLF, measured at backreflected power level exceeding Rayleigh background by 20 dB, exhibits 2.1-dB (2.2-dB) increase compared to 100-m-long DF-HNLF (DD-HNLF), as shown in Fig. 2b. The 250-m-long DF-DD-HNLF at TT has SBS threshold 2.1 dB higher than at that at RT and about 2 dB higher than that of 100-m-long DF-HNLF and DD-HNLF. In fact, the SBS threshold of the 250-m-long 5-segment fiber at TT is only 0.3 dB lower than that of 100-m DF-DD-HNLF, even though it uses 3× longer DF and 2× longer DD sections, proving that temperature detuning prevents SBS accumulation with distance.

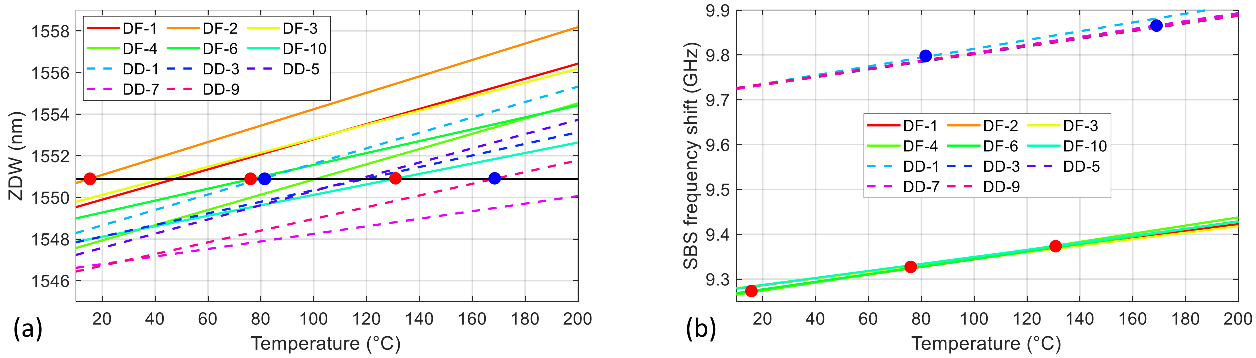

Fig. 1. Linear fits to measured (a) temperature dependence of ZDW and (b) temperature dependence of the SBS frequency shift.

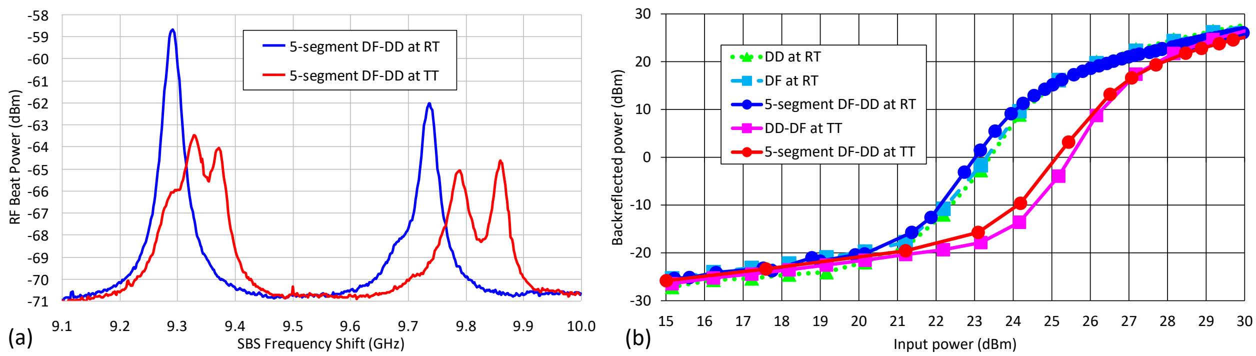

Fig. 2. (a) SBS spectra of 250-m-long 5-segment HNLF for temperature tuning (TT) and room temperature (RT). (b) SBS backreflected power for 250-m-long 5-segment HNLF (RT, TT), as well as 100-m-long DF-HNLF (RT), DD-HNLF (RT), and DF-DD-HNLF (TT).

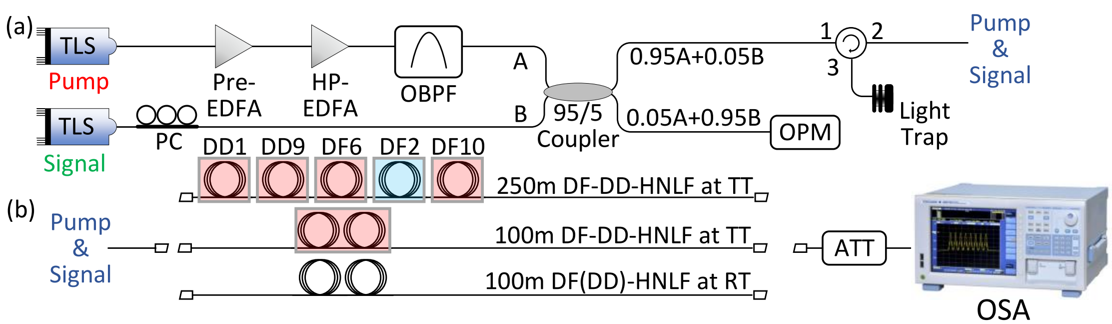

Fig. 3. Experimental setup for OPA performance characterization of the four HNLFs under test. ATT: attenuator; EDFA: Erbium-doped fiber amplifier; HP: high power; OBPF: optical bandpass filter; OSA: optical spectrum analyzer; PC: polarization controller; TLS: tunable laser source; OPM: optical power meter. Pink pads: heaters, blue pad: thermoelectric cooler (TEC).

The experimental setup for characterization of the OPA performance with three 100-m-long and one 250-m-long HNLFs is shown in Fig. 3. Pump light from a tunable laser source (TLS, Ando AQ4321A) goes through two erbium-doped fiber amplifiers (EDFAs): pre-amplifier (pre-EDFA) and high-power EDFA (HP-EDFA). Two cascaded 1-nm-wide optical bandpass filters (OBPF, Koshin Kogaku) after the EDFAs block the out-of-band amplified spontaneous emission (ASE). Another TLS serves as the signal and is aligned in polarization with the pump by a polarization controller (PC). 95% of the pump and 5% of the signal are combined by a 95/5 coupler and sent to the HNLF under test through a circulator that deflects the SBS-backreflected light into a light trap (Thorlabs FTAPC1). For temperature tuning of HNLFs we use DC heating pads controlled by PID circuits and (for DF-2 only) a thermo-electric cooler (TEC). A thermal insulation layer wrapped outside of heating pad or TEC ensures uniform temperature distribution. The HNLF output, after attenuation (ATT), is observed by an optical spectrum analyzer (OSA).

The OPA performance is measured with phase-dithering-free CW pump (200 kHz linewidth) set to the wavelength yielding widest and highest gain (ZDW + 1 nm for the 100-m-long and ZDW + 2 nm for 250-m-long HNLFs). We fix the input pump power at 30 dBm (well above the SBS thresholds for all HNLFs under test), so that the OPA performance is determined by the corresponding SBS threshold. The best indicator of the OPA performance is the CE, defined as the ratio of the output idler and input signal powers.

The measured CEs of the three 100-m-long HNLFs (DF-DD-HNLF at TT, DF-HNLF at RT, and DD-HNLF at RT) and the 250-m-long 5-segment DF-DD-HNLF at TT are shown in Fig. 4. Compared to 100-m-long single fiber (DD or DF) cases, the 100-m-long DF-DD-HNLF yields from 1.2 dB to 4.7 dB higher CE and wider bandwidth [13]. Since 250-m-long 5-segment DF-DD HNLF at TT increases the fiber length while keeping the SBS threshold essentially the same as that for 100-m-long DF-DD-HNLF, its peak CE is ~10 dB higher than maximum CE for 100-m-long DF-DD-HNLF at TT, with 3-dB bandwidth of 20 nm.

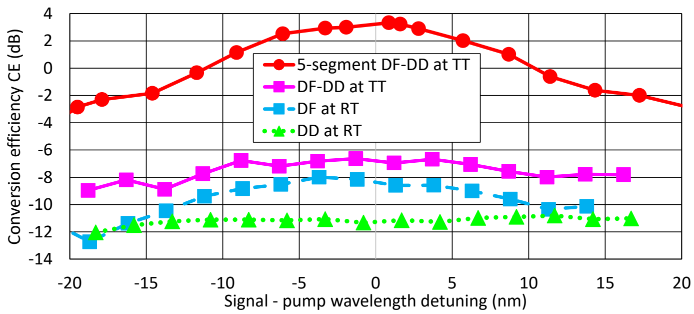

Fig. 4. SBS-limited conversion efficiency (CE) vs signal-pump wavelength detuning with 1 W CW pump located at ZDW + 1 nm (100-m-long DF-DD-HNLF at TT, DF-HNLF at RT, and DD-HNLF at RT) or ZDW + 2 nm (250-m-long 5-segment DF-DD-HNLF at TT).

3. Conclusion

We have shown that by combining two types of HNLFs with different SBS frequencies and further detuning SBS frequencies of several segments within the same type of HNLF by temperature while simultaneously aligning their ZDWs, we can increase the fiber length 2.5 times and raise its SBS threshold by 2 dB, compared to an HNLF of a single type with no temperature tuning. This increases SBS-limited CE by over 10 dB, yielding CE > 0 dB over 22-nm-wide bandwidth and enabling practically useful CE levels without pump phase modulation.

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5. References

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