Temperature-tuned two-segment highly-nonlinear fiber with increased stimulated Brillouin scattering threshold

Cheng Guo,[1] Michael Vasilyev,[1*] Youichi Akasaka,[2] Paparao Palacharla,[2] Shigehiro Takasaka,[3] and Ryuichi Sugizaki[3]

[1]*Department of Electrical Engineering, University of Texas at Arlington, Arlington, TX, USA*
[2]*Advanced Technology Labs, Fujitsu Network Communications, Richardson, TX, USA*
[3]*Furukawa Electric Co. Ltd., Ichihara, Chiba, Japan*
*vasilyev@uta.edu

Abstract: We apply temperature tuning to align zero-dispersion wavelengths of two fiber segments with different Brillouin frequencies. The resulting two-segment highly-nonlinear fiber exhibits 2.1-dB-increased stimulated Brillouin scattering threshold and flattened parametric gain.

1. Introduction

Fiber-optic parametric amplifiers utilize large nonlinear coefficient and low loss of highly-nonlinear fiber (HNLF) to enable 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 limited CW pump power results in low wavelength conversion efficiency (CE), which narrows OPA's range of applications. The SBS threshold in the HNLF can be increased by broadening the Brillouin gain spectrum, for which different 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, none of these solutions is free of compromises: 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 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 this paper, we extend our approach [12] of increasing SBS threshold while aligning ZDWs with temperature tuning by making a customized HNLF. The customized HNLF consists of a segment of dispersion-decreasing (DD) HNLF [12] and a segment of dispersion-flattened (DF) HNLF [13]. DD-HNLF and DF-HNLF have different SBS shift frequencies, but can be spliced together with < 0.1 dB splice loss. After characterizing temperature-dependent ZDWs and SBS frequency shifts using measurement techniques of [12], we employ a single fiber heater to align the ZDWs of the two segments of the customized HNLF at 40°C (1/3 of the tuning range used in [12]). We demonstrate higher SBS threshold and higher achievable wavelength-conversion efficiencies with CW pump in the temperature-tuned customized HNLF, compared to the same length of DF-HNLF or DD-HNLF alone.

2. Fiber characterization and thermal-tuning experiments

Figure 1 shows the temperature tuning curves for (a) ZDWs and (b) SBS frequency shifts for segments of DD-HNLF (4 segments) and DF-HNLF (10 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 25°C to 80°C at 5°C intervals. Based on these plots, we select 3 segments of DD-HNLF and 3 segments of 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-2 and DD-3, both of which have 1547.3 nm ZDW and 9.77 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 9.3 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-1, whose tuning curves yield equal ZDWs of 1547.8 nm and two separate SBS gain peaks (9.31 GHz for DF-4 and 9.78 GHz for DD-1, as shown in Fig. 2a) at 40°C.

With such thermal tuning (TT), the SBS threshold of 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 experimental setup for characterization of the OPA performance with three 100-m-long HNLFs is shown in Fig. 3. Pump light from a tunable laser source (TLS, Ando AQ4321A) passes through a polarization controller (PC) and 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 (OBPF, 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 tuning the PC in the pump path. 90% of the pump and 10% of the signal are combined by a 90/10 coupler and sent to HNLF under test through a circulator that deflects the SBS-backreflected light into a light trap (Thorlabs FTAPC1). The customized HNLF is temperature-tuned with a DC heating pad controlled by PID circuit. A thermal insulation layer is wrapped outside of DC heating pad to ensure uniform temperature distribution within the heating unit. 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 positioned at ZDW or ZDW+1nm for the three 100-m-long HNLFs under test. The CW pump has a narrow linewidth (200 kHz), and the OPA is limited by the SBS. We fix the input pump power at 30 dBm, which is well above the SBS thresholds for all 3 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 unity, and the best indicator of the OPA performance is the conversion efficiency (CE) at the idler wavelength.

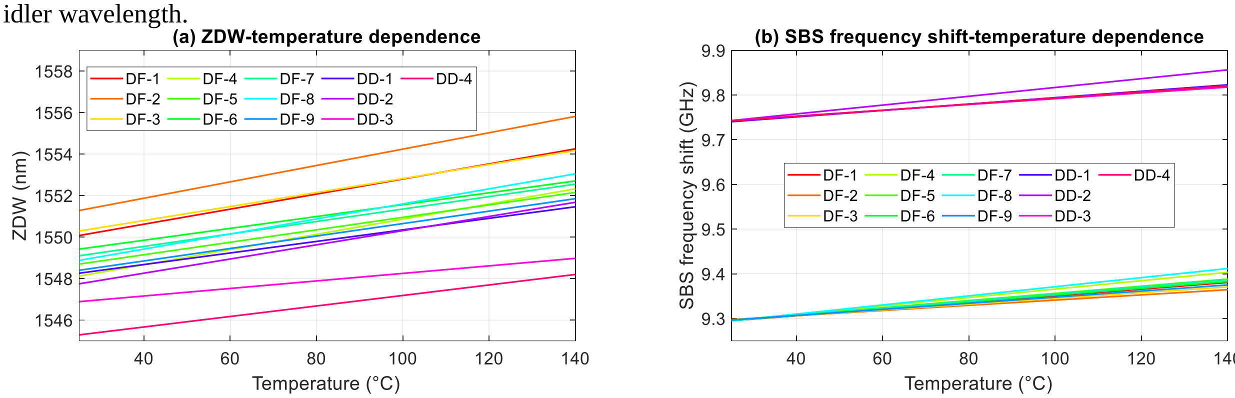

Fig. 1. (a) Linear fits to measured temperature dependence of ZDW; (b) linear fits to measured temperature dependence of the SBS frequency shift.

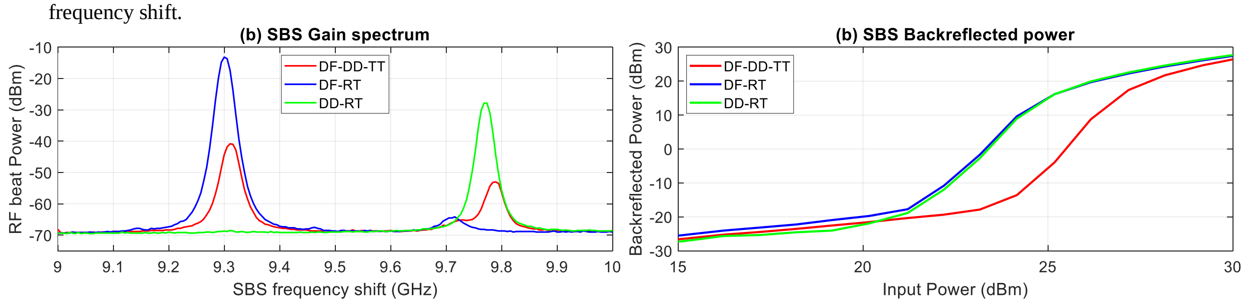

Fig. 2. (a) SBS gain spectra for the customized HNLF with temperature tuning (TT), DF-HNLF at room temperature (RT), and DD-HNLF at RT. (b) SBS backreflected power for the customized HNLF at TT, DF-HNLF at RT, and DD-HNLF at RT.

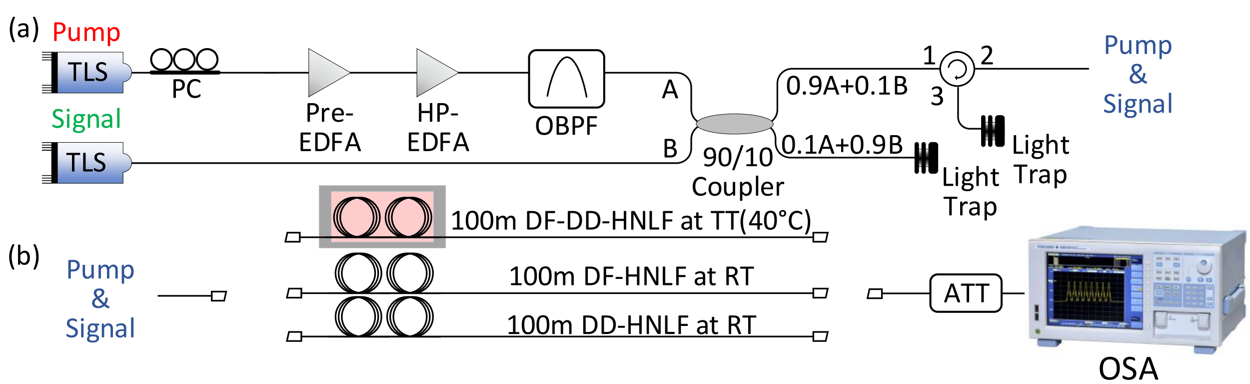

Fig. 3. Experimental setup for OPA performance characterization of the three HNLFs under test. ATT: attenuator; EDFA: Erbium-doped fiber amplifier; HP: high power; OBPF: optical bandpass filter; OSA: optical spectrum analyzer; PC: polarization controller; TLS: tunable laser source.

The OPA performance of the customized fiber (DF-DD-HNLF), DF-HNLF, and DD-HNLF with the pump placed at ZDW and ZDW + 1 nm is shown in Fig. 4. Compared to DF-HNLF and DD-HNLF, the CE of the customized HNLF is higher by 1.0 dB … 3.2 dB over 30 nm bandwidth, and the 1-dB gain bandwidth is improved from 6.5 nm to 15 nm, for the pump placed at ZDW. When the pump is placed at ZDW + 1 nm, the customized HNLF's CE is higher by 1.2 dB … 2.5 dB over 30 nm bandwidth, and the 1-dB gain bandwidth is improved from 7 nm to 14 nm, compared to DF-HNLF and DD-HNLF. The results indicate that the combination of DF-HNLF and DD-HNLF segments not only improves the CE by increasing the SBS threshold, but also flattens the gain curve by combining two dispersion profiles.

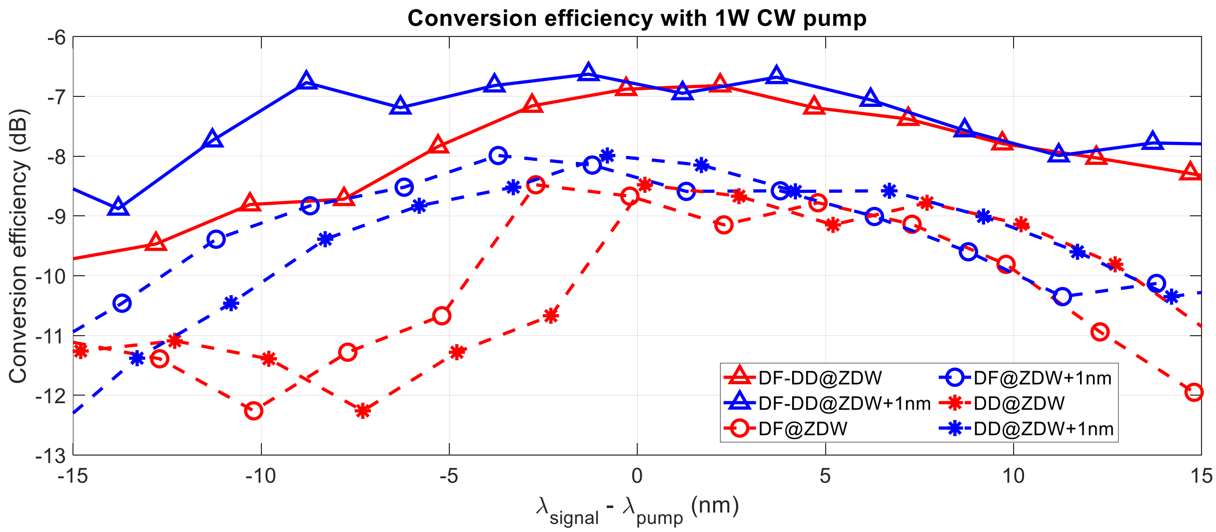

Fig. 4. Conversion efficiency with 1 W CW pump located at ZDW (red) and ZDW + 1 nm (blue) for the customized DF-DD-HNLF at TT, DF-HNLF at RT, and DD-HNLF at RT, as a function of signal-pump wavelength detuning.

3. Conclusion

We have shown that both SBS threshold and OPA gain and flatness of an HNLF can be simultaneously improved by a customized HNLF consisting of fiber segments with very different SBS frequency shifts by applying thermal tuning to align their ZDWs. This opens a possibility of obtaining gain-flattened OPA and avoiding the need for pump phase modulation by combining different types of HNLF.

4. References

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