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Gain optimization in fiber optical parametric amplifiers by combining standard and high-SBS threshold highly nonlinear fibers

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Abstract: Combining Al-doped and Ge-doped HNLFs as gain media in FOPAs is proposed and optimized, resulting in efficient SBS mitigation while circumventing the additional loss of the high SBS threshold Al-doped fiber.

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1. Introduction

Fiber optical parametric amplifiers (FOPAs) have triggered a significant interest due to their ability to provide high gain and large gain bandwidth at arbitrary wavelengths depending solely on the pumping scheme and dispersion properties of the fiber used as the gain medium. Furthermore, when used in a phase-sensitive configuration, FOPAs are attractive for optical regeneration or ultra-low noise amplification [1]. One of the main practical limitations of FOPAS is the need for high pump powers giving rise to strong stimulated Brillouin scattering (SBS). SBS is indeed detrimental because the backscattered power depletes the pumps, subtracting power to be transferred to the signal and thus decreasing the gain. Different strategies have been proposed to overcome this impairment, including broadening the pumps spectra through phase modulation, combining fibers with non-overlapping SBS gain spectra, or exploiting fibers with enhanced SBS threshold [2] such as the recently demonstrated Al-doped fiber [3]. For phase sensitive applications, phase-modulating the pumps is obviously not desirable and consequently most of the recent breakthroughs in this areas have been demonstrated using Al-doped fibers, which however present enhanced loss of the order of 15 dB/km and reduced nonlinear coefficient, thus effectively preventing net parametric gain from being achieved. In this study, we propose to combine standard Ge-doped and high-SBS threshold Al-doped highly-nonlinear fibers (HNLFs) to simultaneously achieve SBS reduction and net positive gain. Furthermore, we optimize this scheme with respect to the two types of fibers lengths and show how phase sensitive processes in the second fiber contribute to the overall gain.

2. Method

Throughout this study, a single pump FOPA is considered. A 30 dBm continuous wave (CW) pump at 1560 nm is injected together with a −50 dBm CW signal into a sequence of Al-doped HNLF (Al-HNLF) of length RL_T followed by a length $(1-R)L_T$ of Ge-doped HNLF (Ge-HNLF), where L_T is the total fiber length. The low signal input power ensures that the FOPA gain remains unsaturated and that the signal itself is not affected by SBS. The numerical model implemented to describe the effect of SBS follows [4]. The coupled power equations for the pump and Stokes waves have been solved through a shooting algorithm and the knowledge of the Stokes power evolution has been incorporated into the split-step Fourier method to solve the nonlinear Schrödinger equation describing the propagation through the fibers. The Stokes power evolution has been calculated independently for the two HNLF sections since there is no overlap between their SBS gain spectra, the difference between their Brillouin shifts being larger than their Brillouin linewidths [3]. The typical values of the HNLFs parameters follow those reported in [3]. The Al-HNLF dispersion and dispersion slope at 1560 nm, loss, nonlinear coefficient, Brillouin gain and Brillouin shift are equal to 0.04 ps/(nm·km), 0.011 ps/(nm^2·km), 15 dB/km, 7.4 W^{-1}·km^{-1}, 1.668×10^{-12} m/W and 11.71 GHz, while for the Ge-HNLF these parameters are taken equal to 0.26 ps/(nm·km), 0.018 ps/(nm^2·km), 0.83 dB/km, 11.6 W^{-1}·km^{-1}, 5.675×10^{-12} m/W and 9.36 GHz respectively. Fig. 1(a) shows the calculated SBS threshold as a function of fiber length for both Ge- and Al-HNLFs. The SBS threshold is defined here as the fiber input power P_{th} such that the backscattered Stokes power at the fiber input is equal to $0.01\times P_{\text{th}}$. The calculations accurately reproduce the experimental data in [3], thus validating our model, and confirm the enhanced threshold of the Al-HNLF, hence the choice of the fiber order in the FOPA.

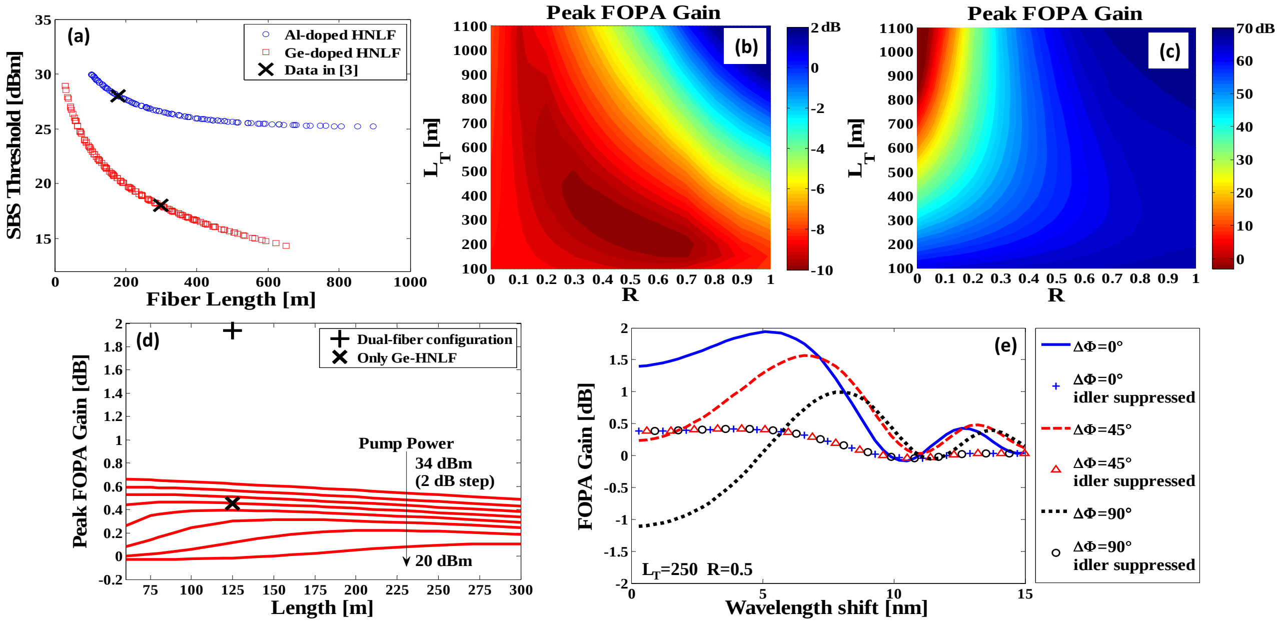

Fig. 1. (a) SBS Threshold for Al- and Ge-HNLFs and comparison with [3]; Peak FOPA gain with (b) and without (c) SBS effects considered; (d) Peak FOPA gain in the Ge-HNLF alone for various pump powers and maximum gain for the dual-fiber configuration; (e) FOPA gain spectrum: effect of pump-signal phase difference ΔΦ with and without idler suppression at the Ge-HNLF input.

3. Results and discussion

The peak FOPA gain was calculated as a function of L_T and R with (Fig. 1(b)) and without (Fig. 1(c)) taking SBS into account. As expected, a higher gain is reached when SBS is not depleting the pump. When SBS is neglected, Brillouin gains are set to zero, the gain increases when R tends towards zero. A higher gain is indeed reached without Al-HNLF, due to its higher loss and lower nonlinearity. However, considering SBS, an optimum length ratio R is found. The Al-HNLF thus contributes to the gain and may even result in a positive net gain (maximum value for $L_T = 250$ m and $R = 0.5$), not obtainable with Al-HNLF alone (loss limit) or Ge-HNLF alone (SBS limit). A further gain increase is expected by tailoring the dispersion of the two HNLFs so that they present identical phase-matched wavelengths.

To further analyze this result, the parametric gain peak has been calculated for various pump powers using the Ge-doped HNLF alone. Figure 1(d) shows the results and compares them with the optimum value obtained with the dual-fiber configuration. This optimum is achieved with 28 dBm of pump power input to the second Ge-doped stage. For the same pump power, the Ge-HNLF alone shows almost no gain (black cross) and the use of a dual-stage increases the amplification. Even though, in the first stage the gain merely compensates the losses, four-wave mixing produces a strong idler which is injected into the second fiber, thus resulting in a phase sensitive amplification process. This is confirmed in Fig. 1(e) where the parametric gain spectra for $L_T = 250$ m and $R = 0.5$ are calculated after artificially introducing a phase shift ΔΦ between signal and pump at the second stage input. The phase sensitivity of the total gain is clearly seen. Furthermore, if the idler is artificially suppressed at the first stage output, the phase sensitivity vanishes and the peak gain is reduced to the value of Figure 1(d), black cross.

4. Conclusion

Combining high-SBS threshold Al-HNLF with low-loss Ge-HNLF has been shown to result in effective SBS suppression while enabling parametric gain improvement over the use of Al-HNLF alone, which is severely limited by fiber loss. The scheme is particularly attractive for phase-sensitive signal processing, where the traditional SBS mitigation method by phase dithering of the pump is not applicable.

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