Phase-Sensitive Amplification in Optical Fibers

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Abstract: We describe the progress in fiber-based phase-sensitive parametric amplifiers in both frequency-degenerate and frequency-nondegenerate configurations. We discuss their applications for phase regeneration, as well as for lumped and distributed noiseless amplification.

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Phase-sensitive amplifiers (PSAs) have unique properties that allow them to break the 3-dB quantum limit of the optical amplifier noise figure [1], as well as provide the phase regeneration leading to suppression of frequency and timing jitters in optical transmission lines [2,3]. The first experimental demonstrations of sub-3-dB noise-figure (NF) PSAs were done in $\chi^{(2)}$-based devices [4,5]. The free-space bulk-crystal PSA also enabled noiseless amplification of images [6]. PSA's use in optical communication context, however, requires fiber-based approaches. One of such designs, based on a nonlinear optical loop mirror (NOLM), was introduced in [7] and successfully utilized in [8] for soliton regeneration in a long-term storage buffer. The solutions to synchronization of the pump and incoming signal phases were developed via pump injection locking [9] and optical phase-locked loop [10].

Achieving the sub-3-dB NF in fiber-based PSAs, however, is challenged by the Guided Acoustic-Wave Brillouin Scattering (GAWBS) that introduces uncorrelated phase fluctuations in the counter-propagating NOLM arms, resulting in amplitude noise at the PSA output. The nearly noiseless PSA performance has nevertheless been experimentally demonstrated in [11,12], using pulses with orthogonal polarizations to cancel common GAWBS noise, followed by [13], where the GAWBS was avoided by conducting the NF measurements well above this noise's cut-off of ~2 GHz. Despite these successes, the complexity of GAWBS mitigation clearly limits the potential use of the NOLM-based PSAs. Even more importantly, the NOLM-based PSAs are inherently single-channel devices not compatible with modern wavelength-division-multiplexed (WDM) transmission systems.

The above two drawbacks can be overcome in the new-generation fiber PSAs that are based on non-degenerate four-wave mixing (FWM) in fiber. By exciting a combination of the signal and idler waves at the input, such an optical parametric amplifier can be put into a phase-sensitive regime. Moreover, two independent modes involving signal-idler-wave combinations can be phase-sensitively amplified at the same time, resulting in the same bandwidth utilization as that of the frequency-degenerate PSA. Since all involved waves propagate in the same direction, the GAWBS perturbs all of them equally, with no impact on the PSA gain and noise. In addition, by using the wide-bandwidth parametric amplifiers (e.g. those involving two pumps [14]), one can simultaneously amplify many WDM channels, provided that their phases are synchronized up to a multiple of π. In-depth analysis of NF of these devices indicates their potential for beating the 3-dB NF quantum limit [15–17]. Recently, a FWM-based phase-sensitive gain has been experimentally demonstrated using pump modulation sidebands as the signal and idler [18].

In the talk, we will discuss the progress in FWM-based PSAs, and their extension to distributed amplification, where they can improve the NF beyond the limit of an ideal distributed amplifier reached recently in [19–21].

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