Recent Advances in Fiber Optical Parametric Amplifiers for Optical Communications

Vladimir Gordienko
Aston Institute of Photonic Technologies
Aston University
Birmingham, UK
v.gordienko1@aston.ac.uk

Florent Bessin
Laboratoire de Photonique d'Angers
Université d'Angers
Angers, France
florent.bessin@univ-angers.fr

Mariia Bastamova
Aston Institute of Photonic Technologies
Aston University
Birmingham, UK
210114416@aston.ac.uk

Sonia Boscolo
Aston Institute of Photonic Technologies
Aston University
Birmingham, UK
s.a.boscolo@aston.ac.uk

Nick J. Doran
Aston Institute of Photonic Technologies
Aston University
Birmingham, UK
n.j.doran@aston.ac.uk

Andrew D. Ellis
Aston Institute of Photonic Technologies
Aston University
Birmingham, UK
andrew.ellis@aston.ac.uk

***Abstract*—We review recent advances in fiber optical parametric amplifiers: demonstrate Mach-Zehnder architecture for polarization-insensitive operation with improved noise figure and reduced nonlinear crosstalk, show reduction of signal penalties due to pump phase modulation, and demonstrate waveband-shift-free optical phase conjugation in a nonlinear optical loop mirror.**

Keywords—fiber optical parametric amplifier, optical communications, optical phase conjugation, nonlinear optical loop mirror

I. INTRODUCTION

Fiber optical parametric amplifiers (FOPAs) have a range of unique features making them an appealing amplification technology for future optical communications. Some of these features are: ability to operate in virtually any frequency bands and with virtually unconstrained gain bandwidth, ultra-fast response time (~0.1 fs), ability for phase-sensitive amplification, wavelength conversion and phase conjugation, etc. [1].

However, FOPAs' application in optical communications requires overcoming several challenges. The key of them are FOPAs' polarization sensitive gain, limitations imposed by stimulated Brillouin scattering, unwanted four wave mixing (FWM) products (including nonlinear crosstalk), and the necessity to use high power pumps leading to low power efficiency.

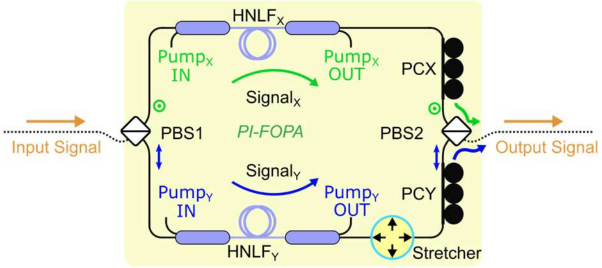

Fig. 1. A scheme of polarization-insensitive fiber optical parametric amplifier employing a Mach-Zehnder architecture.

In this paper we review recent advances addressing three out of four challenges highlighted above. In Section II we describe a promising Mach-Zehnder architecture for polarization-insensitive (PI) FOPA allowing for lower noise figure and nonlinear crosstalk than currently used looped PI-FOPA. In Section III we demonstrate reduction of signal penalties caused by pump phase modulation employed for mitigation of stimulated Brillouin scattering. In Section IV we demonstrate a nonlinear optical loop mirror to demultiplex signals from FWM products over a broad band and thus to perform a waveband shift-free optical phase conjugation. We believe that these and future advances in FOPA technology will stimulate development of nonlinear gain media allowing to reduce FOPA pump powers and improve FOPA power efficiency.

II. MACH-ZEHNDER ARCHITECTURE FOR PI-FOPA

A looped polarization diversity scheme for FOPA [2] has enabled a significant advancement of a PI-FOPA technology [3]. However, amplified signals in looped PI-FOPAs pass an additional length of highly nonlinear fiber (HNLF), which increases insertion loss, nonlinear crosstalk and noise figure [4]. Therefore, we have proposed and demonstrated a Mach-Zehnder (MZ) architecture for PI-FOPA, where signals are recombined after amplification as shown at Fig. 1 [5]. This avoids the shortcomings of an additional HNLF length but presents a challenge of matching MZ-PI-FOPA arm lengths.

We have shown that a fiber stretcher can be used to match MZ-PI-FOPA arms' lengths with precision of ~0.3 mm. This is equivalent to delay of ~1.5 ps, which contributes to polarization mode dispersion and can be compensated by digital signal processing. Then, we have used this MZ-PI-FOPA to

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This work was supported by UK EPSRC projects EP/R024057/1 (FPA-ROCS), EP/S016171/1 (EEMC), EP/T518128/1 (DTP), EP/S003436/1 (PHOS), and EP/X019241/1 (CREATE), and H2020 MSCA (713694).

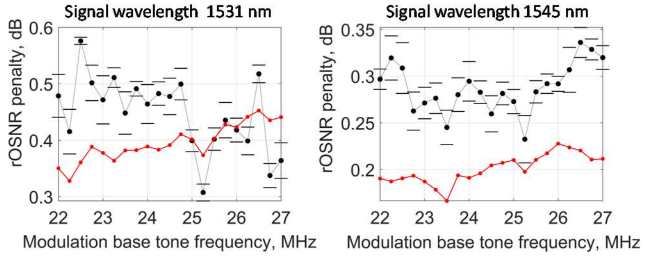

Fig. 4. Experimental (black) and simulated (red) required OSNR penalty as a function of pump phase modulation frequency. frequencies lead to much lower rOSNR penalty due to partial compensation.

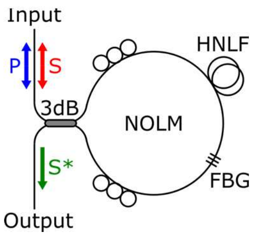

Fig. 2. A scheme of a broadband waveband-shift-free OPC in NOLM.

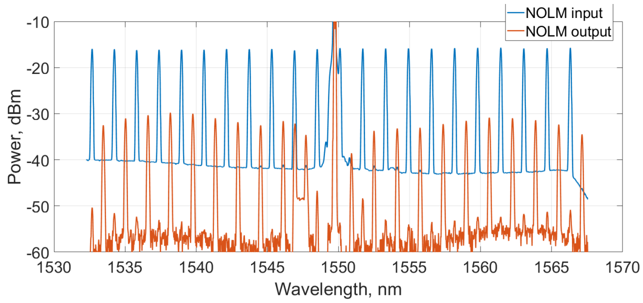

Fig. 3. Experimental optical power spectra at the input and output of OPC in NOLM show that signal conjugates are transmitted to the output, while signals and the pump are supressed at the output.

demonstrate net gain of 16…24 dB, noise figure of 4.5…5.5 dB and reduced nonlinear crosstalk when amplifying WDM signals across bandwidth of at least 13 nm. This demonstration confirms the Mach-Zehnder polarization-diversity architecture to be the most promising for future PI-FOPA experiments.

III. REDUCTION OF IMPACT OF PUMP PHASE MODULATION ON QAM SIGNALS IN PI-FOPA

Pump phase modulation is the most efficient technique to mitigate stimulated Brillouin scattering in FOPAs [6]. We have examined its impact on QAM signals in polarization diverse FOPAs and found that it is the dominant source of signals' distortion [7]. However, we have also found that features of a polarization-diversity architecture can be used to mitigate the impact of pump phase modulation on amplified signals. We have fine-tuned pump phase modulation frequencies to utilize this feature and thus about halved the required OSNR penalty (Fig. 2). Overall, the required OSNR penalty was 0.2…0.45 dB across the PI-FOPA operation range, and it can be reduced further by employment of digital signal processing to mitigate the induced distortions [8].

IV. WAVEBAND-SHIFT-FREE OPTICAL PHASE CONJUGATION IN NONLINEAR OPTICAL LOOP MIRROR

Another direction of our work are interferometric FOPAs allowing to separate signals and FWM products even if they occupy the same waveband. This approach can be used to mitigate nonlinear crosstalk or to separate signals and idlers [9]. We have performed an experiment to demonstrate the latter in the context of a waveband-shift-free optical phase conjugation (OPC) [10]. In this experiment we perform OPC in an asymmetric nonlinear optical loop mirror (NOLM), whereas signals (S) are reflected from the NOLM and their conjugates (S*) are transmitted through the NOLM (Fig. 3). The broadband operation is ensured by employment of a fiber Bragg grating based phase shifter to introduce an asymmetry in otherwise symmetric NOLM. We demonstrate signal and pump suppression at the NOLM output >35 dB and an extinction ratio between signal conjugates and signals of 17…25 dB across most of the examined 35 nm wide band (Fig. 4). This confirms a great potential of interferometric FOPAs for broadband applications in amplification, optical phase conjugation, wavelength conversion, etc.

ACKNOWLEDGMENT

We thank Dr S. Takasaka and Dr R. Sugizaki of Furukawa Electric for HNLFs, and Dr C. Laperle of Ciena for the transponder.

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