S-Band Amplification and S- to C/L-Band Wavelength Conversion Using a TDFA/FOPA Hybrid Amplifier

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Abstract

A novel type of hybrid amplifier/wavelength converter is presented, coupling a TDFA and a FOPA module in series. Signal amplification over the entire S-Band (1450-1530 nm) and signal-to-idler conversion from 1540-1630 nm is demonstrated.

Introduction

Data, internet, and voice traffic experience a steady increase. Three pathways to accommodate the growing information flow are: data rate increase, channel spacing reduction, and expansion of currently used C-band towards its short (S-Band) and long (L-Band) wavelength range.

Exploring band plan expansion two challenges arise: Optical signal amplification and wavelength conversion. Er$^{3+}$-doped fiber amplifiers (EDFA), used in C-band communications, can easily be adapted for L-band operation. For the S-band other amplifiers are required. The Tm$^{3+}$-doped fiber amplifier (TDFA) is a promising candidate. As far as optical wavelength conversion is concerned, periodically poled LiNbO$_3$, semiconductor optical devices, and fiber optical parametric amplifiers (FOPA) are the aspirants. FOPAs have the advantage of being fiber-based and offering high gain and conversion efficiency. To increase gain and conversion bandwidth, combinations of optical amplifiers and wavelength converters have been studied, e.g. Raman-enhanced FOPAs [1,2]. Recently, an EDFA-FOPA pre-amplifier hybrid has been reported, improving the system power penalty by using the FOPA as optical limiter [3].

In this work we present a hybrid amplifier and wavelength converter consisting of a TDFA and a FOPA module in series. We study the individual modules, their contribution in the hybrid, and the overall performance of the latter. Amplification over the entire S-band is observed (1460-1530 nm) and wavelength conversion of S-band signals into the C- and L-band (1530-1565 nm and 1565-1625 nm respectively). The noise figure for S-band signals is dominated by the TDFA contribution.

Experimental Setup

The TDFA/FOPA configuration explored consists of a TDFA and a FOPA module in series (see Figure 1). The S-band signal laser is combined with the 1050 nm TDFA pump (Yb$^{3+}$-doped fiber laser) using a 1470/1050 nm fused-fiber coupler (WDM) and fed into the Tm$^{3+}$-doped fiber (TDF). The TDF is 6 m long and doped with 5000 ppm Tm$^{3+}$. It offers more overlap with the gain spectrum of the FOPA than TDFs with lower Tm$^{3+}$ concentration. The amplified signal is then coupled through a circulator into the FOPA stage. The pump of the latter consists of a 1534.86 nm seed laser, whose output is phase-modulated in order to suppress Brillouin scattering, and amplified with an EDFA. The amplified spontaneous emission (ASE) of the EDFA is removed first by a 1 nm band pass filter (BPF), and second by reflected the desired pump wavelength in a fiber Bragg grating (FBG: FWHM 0.4 nm) on the circulator. The FOPA gain medium is a highly nonlinear fiber (HNLF: 0.5 km length, minimum dispersion wavelength $\lambda_0 = 1531$ nm, nonlinear coefficient $\gamma = 11.9$ W$^{-1}$ km$^{-1}$). Polarization controllers (PC) optimize the overlap between pump and signal along the amplifier; isolators (ISO) limit undesired feedback.

The optical performance of the individual TDFA and FOPA modules was studied before the hybrid device was constructed. In the case of the TDFA, the signal pass ended after the optical isolator succeeding the TDF, and was fed into the OSA for analysis. In the case of the FOPA, the signal was directly fed into the FBG-arm of the circulator, without passing through the 1470/1050 coupler and the TDF. To further evaluate their contribution to the hybrid, signal amplification in the hybrid amplifier was investigated with only the TDFA or the FOPA operating.
Results and Discussions

In Figure 2, gain and noise figure contribution of the TDFA module in the hybrid device is shown. The gain peaks around 1475 nm, and reaches 12 dB. The noise figure is as low as 4 dB in the range of maximal gain and increases to both sides. This performance closely mimics that of an individual TDFA, with the gain of the TDFA module in the hybrid being reduced by about 1.5-2 dB due to the additional loss experienced by the circulator and the HNLF.

In Figure 3, the FOPA contribution to the hybrid amplifier is shown. Apart from the S-band amplification (gain and noise figure in Fig. 3.a) the FOPA is used as a wavelength converter (conversion efficiency S- to C/L-band in Fig. 3.b). S-band signal gain is observed in the range from 1512 nm to 1527 nm (Fig. 3.a), as was also found for an individual FOPA with the same amplifier parameters. Signals of shorter wavelength are not amplified by the FOPA and suffer the combined loss of the TDFA and FOPA components, typically around 10 dB. The noise figure is essentially the inverse of the gain spectrum, as expected. The conversion efficiency (Fig. 3.b) is comparable with the gain observed for the signals, proofing the high signal-to-idler conversion efficiency generally achievable in FOPAs.
Figure 3: (a) FOPA contribution to gain (closed circles) and noise figure (open triangles) in the TDFA/FOPA hybrid (see Fig. 1). (b) Signal-to-idler conversion efficiency of the FOPA module (closed squares). Signal input power is 5 \(\mu\)W, FOPA pump power is 590 mW and the TDFA pump is turned off.

Figure 4 presents the amplification and wavelength conversion characteristics of the hybrid. Fig. 4.a shows gain and noise figure in the S-band. The gain curve is essentially a superposition of the gain of the TDFA module (max. of 12 dB at 1475 nm), and of the FOPA module (max. of 10 dB at 1520 nm). 5 dB gain is achieved from 1452 to 1527 nm. A noise figure between 6 and 9 dB is achieved for a band as large as 1450-1520 nm. The rise in the noise figure to the short-wavelength side is due to decreasing TDFA gain and increasing passive component loss, on the long-wavelength side due to the drop in FOPA gain and noise contribution of the FOPA pump. For the noise figure calculation, we followed Freitas [2] and refs. therein, using the formula for single-pump FOPAs to account for the stimulated spontaneous emission of the FOPA over the entire signal range.

Figure 4: (a) Gain (closed circles) and noise figure (open triangles), and (b) conversion efficiency (closed squares). Signal input power is 5 \(\mu\)W, for TDFA and FOPA pump powers are 300 mW and 590 mW. Data for the pure FOPA are also shown (open circles).

The conversion efficiency (see Fig. 4.b) in the range of 1540-1560 nm arises from the well-known four-wave mixing process in the FOPA, matching the gain. In the range 1560-1630, it is reduced by \(-4\) dB, resulting in an asymmetry between gain and conversion efficiency. The fact that S-band signals are still converted into this range arises from their high power after amplification in the TDFA. Placing a signal of comparable power into the L-band (1570-1630 nm) the conversion efficiency is too low to observe an idler in the S-band. Also, the Tm\(^{3+}\), \(^{3}H_{6}\rightarrow ^{3}F_{4}\) transition strongly absorbes signals in this wavelength range.

Multiplexing a total of eight S-band signals and launching into the TDFA/FOPA hybrid simultaneous amplification of all eight channels and S- to C/L-band conversion was observed. In order to reduce detrimental four-wave mixing products between the signals, the signal input power for multi-channel amplification and wavelength conversion has to be comparably low.
Conclusions
We have demonstrated a TDFA/FOPA hybrid for S-band amplification and wavelength conversion to the C/L-band. Following ref. [4], we have tested the addition of 1535 nm pump power to increase the TDFA gain, using part of the EDFA ASE as backward pump the TDFA module. This approach proved detrimental in our case, but may be different in a configuration, where the TDFA module follows the FOPA.

Wavelength conversion of L-band signals into the S-band is not possible in the TDFA/FOPA hybrid amplifier as described here, as the two gain media are separated and the TDFA has no gain in the L-band. One way to optimally profit from both amplification/wavelength conversion mechanisms is to use one single medium offering both types of interaction. Recently, Raman-enhanced FOPAs have been reported exploring this route [1,2].

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