Comparison of Bismuth-Doped Fibre Amplifiers (BDFA) Pumped Using 1195 nm Singlemode Laser Diodes and 950 nm Multimode Laser Diode via YDF-based Conversion Stage

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Abstract *We compared BDFAs directly pumped with 1195 nm single-mode semiconductor laser(s) to 915 nm multimode laser via YDF mode/wavelength conversion stage. We demonstrated that 915/1150 nm pumping have superior performance and lower power consumption compared to 1195 nm.*

Introduction

Bismuth doped fibre amplifiers have been demonstrated to provide gain in O-, E- and S-transmission bands[1-10,14,15]. Recently a BDFA that have more than 20 dB gain between 1345-1460 nm (17.6 THz) covering parts of the O- and E-bands has been demonstrated[1,2] using two single mode pump laser diodes. Despite the impressive bandwidth of 17.6 THz, it is allocated away from the wavelength range standardised for pluggable transceivers (1265-1345 nm)[11]. Moreover, approx. 20% of the demonstrated bandwidth overlaps the OH absorption peak, which reduces the BDFA gain, and increases the noise figure. Amplification over the standardised parts of the O-band has also been demonstrated, although with lower gain compared to the results presented in[1,2,7] and narrower bandwidth[3-5]. Two main drawbacks of BDFAs operating over 1265-1345 nm range are lower BDF power conversion efficiency, compared to the longer signal wavelengths, and pump wavelength location within 1190-1200 nm range. This pump wavelength falls in between InGaAs and InP semiconductor technologies and at present single-mode (SM) pump can only be realised using quantum dot (QD) laser technology that make these pumps less power efficient, more expensive and limited in supply.

Recently, it has been proposed to pump BDFA using commercial-off-the-shelf multimode uncooled high-brightness laser diode via Ytterbium fibre based conversion stage[13]. In this scheme, 915 nm multimode (MM) light is converted into 1150 nm pump by few tens of metres of double-cladding ytterbium doped fibre (YDF). In this paper we directly compare 1195 nm pumped BDFA to 915/1150 nm pumped amplifier. We demonstrated that despite lower power conversion efficiency (PCE) of 1150 nm pumped BDF compared to 1195 nm pump wavelength, same BDF pumped by 915/1150 nm scheme can deliver higher gain and lower noise figure (NF) with same or higher wall-plug efficiency (WPE) compared to cooled 1195 nm SM laser diode (LD) pumped BDFA. In addition, the 915/1150 nm pumping shift the gain peak 20 nm towards shorter wavelength and provide better coverage of industry-standardised part of the O-band that is used for LAN-WDM/CWDM pluggable modules.

Amplifier and BDF design

Figure 1(top) and 1(bottom) shows BDFA design for 1195 and 915/1150 nm pump schemes respectively. In both pump configurations backward pump propagation was used over 170 metres long single BDF stage. In case of 1195 nm pump either single SM LD or two polarisation combined LDs were used to provide up to 750 mW of pump power. The lasers temperature was maintained at 25 ºC using thermo-electric coolers (TEC). The laser has typical threshold current of 50 mA and LI slope efficiency of 0.41 W/A while overall electrical-to-optical power conversion efficiency slope was 0.09 at 300-600 mW LD output power range (Fig. 2). For fair comparison, two separate WDMs with similar bandwidth centred at gain peak wavelengths of 1320 and 1300 nm were used for 1195 and 915/1150 pump schemes.

In case of 915/1150 nm pump the multimode uncooled LD pumped the conversion stage consisted of 30 metres long 6/125 YDF, spliced between the high reflection (HR) and output

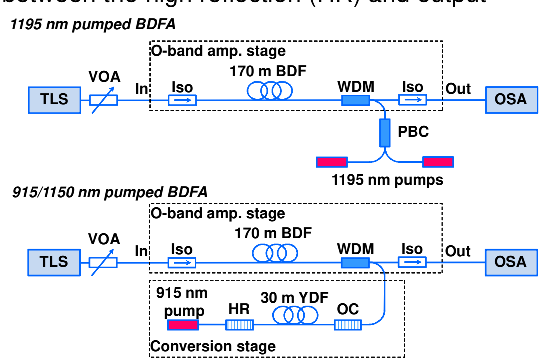

Fig. 1: 1195 nm (top) and 915/1150 nm (bottom) backward pumped BDFA designs; WDM: multiplexer; PBC: polarisation beam combiner; Iso: isolator.

coupler (OC) fibre Bragg gratings (FBG) written with 1 nm 3 dB bandwidth and 99.9% and 75% reflectivity respectively.

A 915 nm 10 W rated MM pump laser was spliced directly to the HR grating. At 20 ºC the pump laser has a threshold current of 510 mA and a LI-slope efficiency of 0.88 W/A that are degraded to 630 mA and 0.82 W/A at 70 ºC. Relatively small laser performance reduction can be explained by selection of operation point below 50% of laser nominal range. The overall electrical to optical power conversion efficiency for the 20-70 ºC temperature range was 0.25-0.20 for up to 2W of 1150 nm power (Fig 2). The conversion stage operates kink-free up to 2.25 W of output power and the kink is caused by pump laser power jump. To generate 2 Watt of 1150 nm power the pump LD current and voltage were 4.6 A and 1.77 V and 5.3 A and 1.84 V for 20-70 ºC respectively. More details about the conversion stage can be found in[12,13].

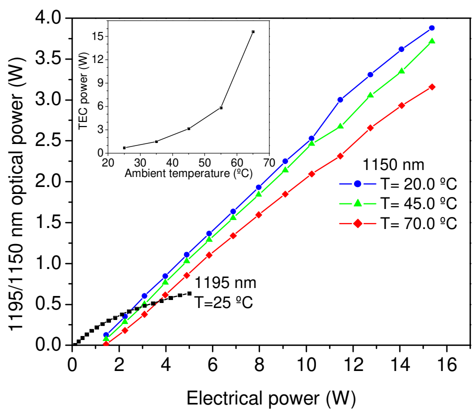

Fig. 2: Conversion stage and semiconductor LD output optical power vs. electrical power. Inset: Semiconductor LD TEC power as a function of ambient temperature.

The O-band stage gain fibre has a bismuth-doped phosphosilicate glass core prepared by modified chemical vapour deposition (MCVD). mode operation mode operation in the O-band.

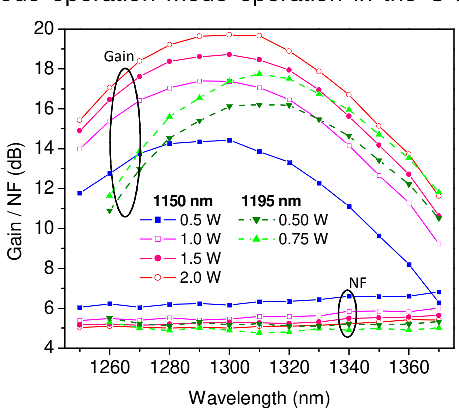

Fig. 3: Gain and noise figure for 0 dBm input signal power.

Core and cladding diameters of the gain fibre are 8 µm and 125 µm respectively. The gain fibre numerical aperture is around 0.13 with cut-off wavelength at 1140 nm, providing single-mode operation in the O-band. The gain fibre loss at 1195nm and 1150 nm wavelengths were 0.032 and 0.044 dB/m respectively.

Amplifier characterisation

To evaluate the BDFA gain and noise figure we used an ASE spectral interpolation method. As shown in Fig. 1, the signal from a low-noise tunable laser source (TLS) was launched into the BDFA under test. At the output of the BDFA the optical spectrum was recorded using an optical spectrum analyser (OSA) and gain and noise figure were computed.

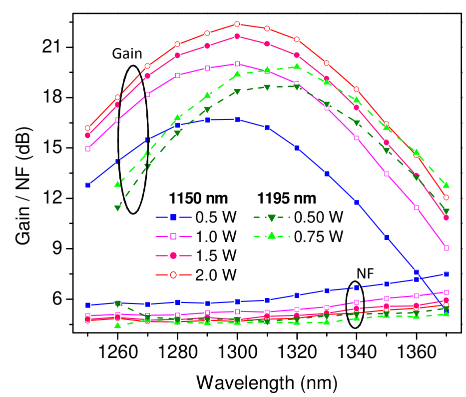

Fig. 4: Gain and noise figure for -20 dBm input power.

Figures 3 and 4 show gain and noise figure for both BDFA pump schemes for 0 and -20 dBm input power respectively. For 1195 nm pump gain peak was at 1320 nm while the amplifier 3 and 6 dB bandwidths were 67 and 100 nm. For 500 mW pump power that is available from single semiconductor LD the peak gain and corresponding noise figure were 16.2 and 5.1 dB respectively for 0 dBm input signal power and 18.7 and 4.8 dB respectively for -20 dBm input power. When two PM combined pump LDs were used yielding 750 mW pump power the gain and noise figure for 0 and -20 dBm input power levels were 17.7 and 4.8 dB and 19.8 and 4.6 dB respectively.

As was suggested in[3], for 915/1150 nm pump scheme the gain peak shifted to 1300 nm while the 3 and 6 dB gain bandwidths were 69 and 102 nm respectively. For 500 mW of 1150 nm pump power the peak gain was 1.9 dB and 2 dB lower and corresponding noise figure 1.1 dB and 1 dB higher compared to 1195 nm pump wavelength for 0 and -20 dBm input signal power. However, since much higher pump power is available for 915/1150 pump scheme even 1W of 1150 nm pumped BDFA will outperform 750 mW 1195 nm pumped BDFA with the highest demonstrated gain and corresponding noise figure at 2W 1150 nm pump power of 19.7 dB and 5.0 dB and 22.4 and 4.7 dB for 0 and -20 dBm input signal power.

It should be noted that according to the loss measurements, approximately 29% and 18% of pump power is unabsorbed in 1195 and 915/1150 pump schemes respectively. In[13] it was demonstrated that FBG after the input isolator can be used to reflect unabsorbed pump to improve the amplifier performance and prevent pump leakage from the amplifier input. Although this solution may be implemented for both pump schemes it may be impractical for the semiconductor laser since either pump reflecting FBG and pump LD wavelength should be closely matched or tens of nm wide FBG should be used to accommodate the pump laser wavelength variation and temperature shift. Therefore we only implemented a pump reflecting grating for 915/1150 nm pumped BDFA. For the peak gain wavelength of 1300 nm the grating improved gain and noise figure by up to 1 and 0.3 dB and 1.5 and 0.3 dB for 0 dBm and -20 dBm input signal power respectively (Fig. 5), while similar improvement was observed over the entire gain bandwidth (not shown due to space limitation).

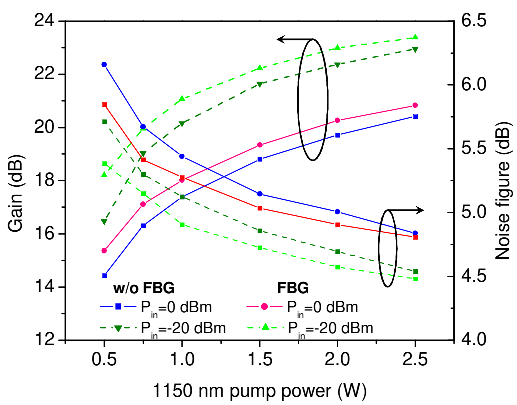

Fig. 5: Gain and noise figure for 915/1150 nm pumped BDFA with and without pump reflecting FBG

Power consumption and summary

Fig. 6 shows BDF power conversion efficiency (PCE) as a function of input signal power for both pump wavelengths. Note for 1195 nm pump PCE was almost constant for 300-500 mW pump power for a given input signal power level. Depending on the input signal power at 500 mW pump power the PCE was between 25 and 35% lower for 915/1150 nm pump scheme compared to 1195nm pump. This difference was reduced to 5 and 20 % if the pump reflecting FBG is added to the 915/1150 nm pumped BDFA. The above PCE figures indicate the amount of extra power for 915/1150 nm pump scheme compared to 1195 nm pump scheme to get similar BDFA performance.

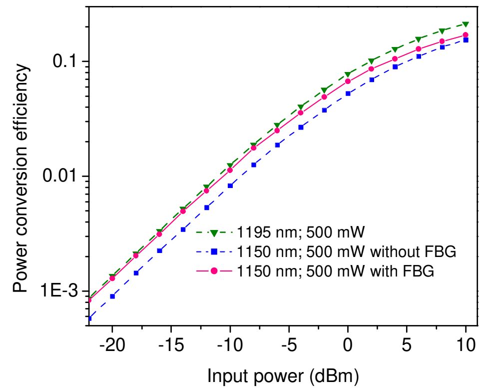

Fig. 6: Power conversion efficiency for both pumping schemes at 500 mW pump power.

However, the electrical-to-optical conversion efficiency slope of 915/1150 nm pump scheme is higher by more than factor of two compared to state-of-the-art semiconductor LD pump for power levels above 250 mW. Note this consideration do not include LD TEC power consumption. Consequently, despite an additional conversion stage and lower BDF PCE, 915/1150 nm pumped BDFA have lower overall power consumption compared to similar performing 1195 nm SM semiconductor LD pumped BDFA even at the room temperature. The inset in Fig. 2 shows 1195 nm LD TEC power as a function of ambient temperature. The sharp increase of TEC power above 40 ºC would further reduce the wall-plug efficiency of 1195 nm cooled LD pumped BDFA increasing the total power consumption by more than factor of 3, while in case of uncooled MM pump used in 915/1150 nm pump scheme the power consumption is only increased by 20% when ambient temperature raised to 70 ºC

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