2013 18th OptoElectronics and Communications Conference held jointly with 2013 International Conference on Photonics in Switching (OECC/PS)

WS1-3

Thulium Doped Fiber Amplifiers for 2 μm Telecommunications

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Abstract

We report the first experimental realization of thulium doped fiber amplifier providing high gain (>40dB), noise figure as low as 5dB and over 100nm wide bandwidth around 2μm with maximum saturated output power of 400mW.

I. Introduction

The thulium (Tm^{3+}) doped fiber amplifier (TDFA) offers a route to significantly enhanced amplification bandwidths. The remarkably broad emission spectrum of the $^3F_4$ – $^3H_6$ transition in Tm-doped silica covers about 30 THz (~1700 to ~2100 nm [9]), which is a particularly attractive feature compared to the ~15 THz (~1480 to ~1610 nm [12]) offered by the $^4I_{13/2}$ - $^4I_{15/2}$ transition in erbium (Er^{3+}) doped silica. Therefore, the enormous potential bandwidth resource of the TDFA is there to be exploited. Despite this Tm-doped fiber amplifiers have received little attention from the optical communication community other than for its S-band emission properties [15]. This is largely due to the lack of a suitable transmission medium, since the background loss of silica fiber is considerable at 2 μm. However, for local area networks, where fiber loss is not a crucial issue, conventional fiber can be used to carry the signals across a significant fraction of the TDFA bandwidth. As for long haul transmission, radically new fiber types will be necessary.

Encouraging developments have recently been reported in the design and fabrication of hollow core photonic band-gap fibers (HC-PBGFs) [18], in which surface scattering at the air-glass interfaces rather than material absorption determines the lowest achievable loss [19]. HC-PBGFs are predicted to exhibit their minimum loss window in the waveband around 2 μm [20, 21], and provide realistic prospects for achieving similar loss levels to conventional fibers at 1.5 μm while maintaining a large transmission bandwidth of more than 100 nm [17, 18]. Moreover, HC-PBGFs possess the advantages of a very low nonlinearity and low latency compared with conventional fibers [17]. Recently, data transmission experiments have been conducted at 2 μm over both conventional solid core fiber and HC-PBGF, achieving 20 Gbit/s [22] and 8 Gbit/s [18] transmission rates, respectively. These preliminary results clearly indicate the potential of 2μm fiber communication systems. It is also worth commenting that other material systems exist with potential for low loss at wavelengths around 2 μm [23-25] providing yet further motivation to consider the telecommunications potential of the TDFA. In this paper, we report the detailed characterization of TDFAs developed for these first transmission experiments and examine their performance over the band ranging from 1910 - 2020 nm for telecom applications. We demonstrate low noise, high gain operation of the TDFA over this entire band indicating that the TDFA is well placed as an amplification medium for 2 μm communication systems.

II. Experimental Setup

Fig. 1. Experimental setup. TLS: tunable laser source. NDF: neutral density filter. L: lens. TDF: Tm^{3+}-doped fiber. WDM: wavelength division multiplexer.

Fig. 1 illustrates the experimental setup of the core pumped Tm-doped fiber amplifier. The TDFA was built with a commercially available Tm^{3+}-doped fiber (OFS TmDF200) having a mode field diameter of ~6.2 μm at 2000 nm and a core absorption of ~20 dB/m at 1565 nm. Two TDFA configurations were developed to provide maximum gain at short and long wavelength bands, respectively. The first design, entitled TDFA-C, consisted of a 12 m long TDF, which was forward pumped by an in-house built fiber Bragg grating (FBG) stabilized single mode Er^{3+}/Yb^{3+} co-doped fiber laser operating at 1565 nm. Pump and signal wavelengths were combined using a 1570 / 2000 nm WDM coupler. Isolators were placed both at the input and output ends to prevent parasitic lasing. The second design, named as TDFA-L, included an additional 4 m TDF (dotted line in Fig.1) inserted between the input isolator and the WDM coupler. This additional piece of fiber was indirectly pumped by the backward-travelling amplified spontaneous emission (ASE) generated from the directly pumped 12m TDF section and provided additional signal gain at longer wavelengths. This pumping scheme is similar to what has been used in L-band EDFA designs [26]. The TDFAs were seeded using an in-house built tunable laser source (TLS) [27]. The laser wavelength was tuned by an external cavity acousto-optic tunable filter (AOTF), providing narrow linewidth wavelength coverage from 1910 nm to 2020 nm. A tunable neutral density filter was used to adjust the input signal power. The free space laser beam from the TLS was coupled to the input end of the TFDAs through an 8 mm focal length lens.

III. EXPERIMENTAL RESULTS

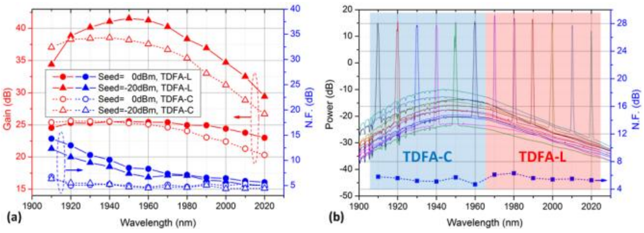

Fig. 2 Performances of TDFA-C and TDFA-L at 31dBm pump power. (a) Noise figure and gain; the solid lines represent TDFA-L, the dotted lines show TDFA-C performance. (b) Output spectra and noise figure when amplifiers were seeded by -10 dBm signal.

Fig. 2(a) compares the (external) noise figure (NF) and gain performances of TDFA-C and TDFA-L respectively at a pump power of 31 dBm. Small (-20 dBm) and saturated (0 dBm) signal gain characteristics for both amplifier configurations are presented. TDFA-C provided a maximum small signal gain of ≥ 38 dB at a peak wavelength of 1930 nm. Whereas the maximum small signal gain of TDFA-L was measured to be 41 dB, ~3 dB higher than TDFA-C due to the added length of gain fiber incorporated in between the input isolator and the WDM coupler, however the gain peak was red-shifted to 1950 nm in this instance. Except for the short wavelength edge of the amplification band, TDFA-L in fact exhibited a small signal gain enhancement approaching ~3-4 dB for wavelengths beyond 1950 nm. Additionally, TDFA-L effectively improved the flatness of the saturated gain curve and consistently provided 23-26 dB saturated gain over the entire amplification bandwidth. In contrast, the saturated gain of TDFA-C dropped significantly for wavelengths above 1960 nm. Note that the gain enhancement offered by TDFA-L on the long wavelength side of the amplification band was achieved without paying any significant penalty in terms of NF. Both amplifier configurations exhibited NFs between 5-7 dB for wavelengths above 1980 nm. However, moving towards the shorter wavelength side, the NF of TDFA-L increased considerably and reached a value of 12-14 dB at 1910 nm, while TDFA-C consistently exhibited 5-6 dB NF over the entire amplification band. Note that even higher gain was available at higher pump power (e.g. 45 dB small signal gain was recorded for TDFA-L at 1950 nm for 32 dBm of pump power), but the system became sensitive to parasitic lasing especially when operating at the edge of the gain band where isolator performance was compromised.

The introduction of the additional indirectly pumped section of gain fiber in TDFA-L therefore had two distinct effects. Firstly, the amplifier gain was notably enhanced, particularly for longer wavelengths, and the saturated gain flatness was improved. This can be attributed to the reabsorption of the otherwise lost backward travelling ASE, which enhanced the amplifier efficiency, and the overall longer length of gain fiber, which shifted the gain peak towards longer wavelengths. Secondly, the NF increased for short wavelengths due to the increased initial absorption of the input signal in the indirectly pumped section before the amplification takes place in the directly pumped gain fiber.

The above discussion suggests that high gain, low noise amplification over the full 110 nm band investigated at 2μm can be achieved by combining TDFA-C and TDFA-L in a transmission system, where shorter wavelength signals up to 1960 nm are amplified by TDFA-C, while TDFA-L provides amplification for the longer wavelengths. The resulting amplified spectra are shown in Fig. 2(b). More than 30 dB small signal gain, NF below 6.3 dB and more than 30 dB optical signal-to-noise ratio (OSNR) were achieved over the entire wavelength range investigated in this work. Note that the amplifier performance could not be investigated below 1910 nm due to the limited tunability of the TLS. Neither the gain curve nor the noise figure in Fig. 2(a) showed any tendency of rapid degradation, which leads us to expect that the true operating window of the TDFAs will ultimately prove to be much broader than that physically demonstrated here: particularly with further customization of the amplifier design and the availability of the sorts of filtering and gain flattening components now routinely available for erbium based systems.

In conclusion, we have demonstrated the performance of two TDFA designs for application as high performance amplifiers in potential future telecommunication networks operating around 2 μm. The TDFAs are analogous in implementation and function to the current EDFA, but capable of operating over a far more extended bandwidth in this new waveband of interest. By choosing two different designs, namely TDFA-C and TDFA-L, optimized for short and long wavelength operation respectively, we were able to demonstrate small signal gains of more than 30 dB and NFs lower than 6.3 dB over a 110 nm bandwidth, and >35 dB gain over 90 nm (1910~2000 nm). The peak gain was measured to be 42 dB at 1950 nm for -20 dBm input signal power at 31 dBm pump power.

ACKNOWLEDGMENT

This work was supported by the EU 7th Framework Program under grant agreement 258033 (MODE-GAP) and by the UK EPSRC through grant EP/I01196X/1 (HYPERHIGHWAY).

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