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A Wide-Band Thulium-Doped Silica Fibre Amplifier *

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We investigate a silica-based thulium-doped fibre amplifier, which is a promising candidate for an amplifying device in the S band, in detail using a single wavelength upconversion pumping scheme centred at 1064 nm. Our experimental results show that in terms of gain and noise figure, the bi-directional pumping scheme is the best one in the three pumping schemes, named forward, backward and bi-directional pumping schemes. The amplifier has a gain not only in the S band, but also in the C band, even in the L band. The gain is above 3 dB from 1525 nm to 1580 nm with a peak of 7.5 dB.

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It is well known that low loss (< 0.3 dB/km) windows of silica optical fibres widely range from 1450 to 1650 nm. The explosive increase in the traffic of optical telecommunications has spurred research efforts on developing highly efficient broadband fibre amplifiers. The so-called S band (1480–1520 nm) becomes more promising as a candidate for the next-generation transmission band. On the one hand, wideband optical amplifiers for the middle-to-longer wavelength region of this window [the so-called C band (1530–1565 nm) and L band (1570–1610 nm)] have been realized by several methods, for example, silica-based erbium-doped fibre amplifiers (EDFAs) and the hybrid EDFA and Raman amplifiers.[1,2] On the other hand, optical signals in the shorter wavelength region can be amplified by thulium doped fibre amplifiers (TDFAs) and Raman amplifiers. Recently, many works have been carried out on TDFAs, but mostly with fluoride-based thulium doped fibres.[3–9] However, the technology of the non-silica glasses is less mature than that of silica ones, which impacts on the efficiency and reliability of non-silica optical fibre amplifiers. Although Cole and Dennis reported the S-band amplification in a thulium-doped silicate fibre,[10] a dual-wavelength (1047 and 1540 nm) pumping scheme was used. However, the complexity of optimization issues of dual-wavelength pumping schemes is doubled with respect to the single-wavelength one. Previously, we reported the experimental results of silica-based TDFA with a single-wavelength pumping scheme.[11,12] In this Letter, we describe how the bi-directionally pumped thulium-doped silica fibre amplifier (TDSFA) can realize amplification in the shorter-wavelength band.

The structure of the bi-directionally pumped TDSFA is shown in Fig. 1. The fibre used in the experiment has the core diameter 4.2 μm, cutoff wavelength 710 nm, numerical aperture (NA) 0.15 and length 12 m. The pump source has stability of smaller than 4% and a nearly diffraction-limited fundamental transverse beam with beam quality $M^2 = 1.1$. The maximum output power is 5 W. The pump power is divided equally by a power splitter. The pump wavelength of the amplifier is 1064 nm. This triggers the up-conversion pumping and forms the population inversion between $^3F_4$ and $^3H_4$ effectively,[3,4] which can overcome the inherent inefficiency of TDFAs due to a shorter lifetime of the upper amplifying level compared with the lower one. Single wavelength up-conversion pumping is a two-step process, in which the first photon populates the lower amplifying level while the second photon is responsible for populating the upper amplifying level via excited state absorption (ESA), simultaneously depopulating the lower level to allow for population. Moreover, the 1064-nm upconversion pumping scheme can suppress the strong 0.8 μm band transition ($^3F_4 \rightarrow {}^3H_6$). The signal sources are ECL-200 (Santec Corporation) and Tunics Purity CL (Nettest Corporation), with the wavelength ranges of 1430–1530 nm and 1525–1625 nm, respectively. The pump and signal fields were multiplexed into and out of the fibre by fusion splicing a fused fibre wavelength division multiplexing (WDM) coupler at both the input and output. Spectra were measured with an optical spectrum analyser (OSA) with resolution of 0.01 nm.

We measured the on–off gain of the device at the output, defined as $G = 10 \log R$, where R is the on/off ratio of the power output. In terms of the gain and noise properties, the bi-directional pumping scheme is proven to be the best one in the three pumping schemes, as shown in Fig. 2. The forward pumping provides lower noise figure due to a high inversion

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rate at the amplifier input, while the backward pumping provides higher power efficiency due to a lower impact of background loss. Bi-directional pumping is then well appropriate because this pumping, by a better distribution of the pump power along the fibre, can reduce the effect of ESA. Note that the present noise figure is negative because the gain increases faster with the pump power than the amplified spontaneous emission power.

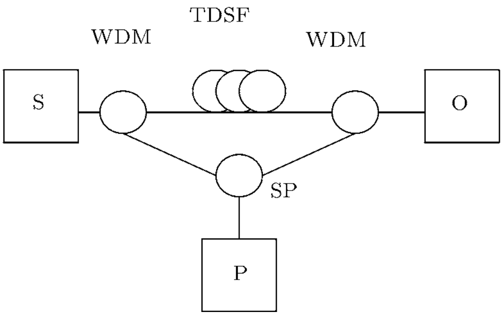

Fig. 1. Diagram of the TDSFA structure. S: signal, P: pump, SP: splitter, O: OSA.

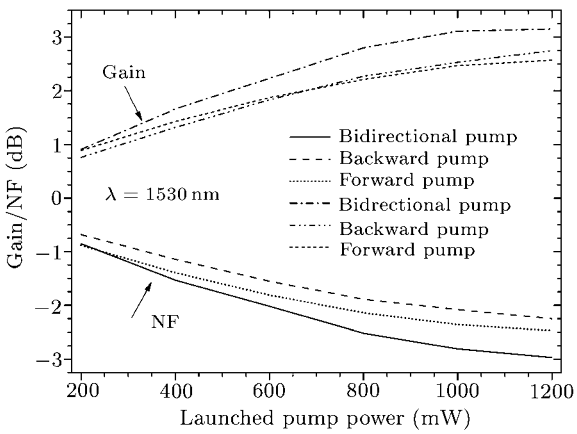

Fig. 2. Comparison of three pumping schemes at the signal wavelength of 1530 nm. NF: noise figure.

Figure 3 shows measured on–off gain as a function of signal wavelength for launched pump powers $P = 400$ mW, 800 mW and 1000 mW, respectively. At the pump power level of 1000 mW, the amplifier has a gain of over 3 dB from 1525 nm to 1580 nm with a peak of 7.5 dB. Figure 4 shows the on–off gain against launched pump power for different signal wavelengths. The amplifier's gain increases fast with the pump power first and then becomes saturated gradually. At the signal wavelength of 1580 nm, the gain increases from 2.6 to 7.5 dB with the launched pump power from 200 to 1000 mW. At the signal wavelength of 1470 nm, the gain is only 0.2 dB even at the maximum pump level because the absorption loss is large at this wavelength. We also measured the variance of noise figure with different signal wavelengths, as shown in Fig. 5.

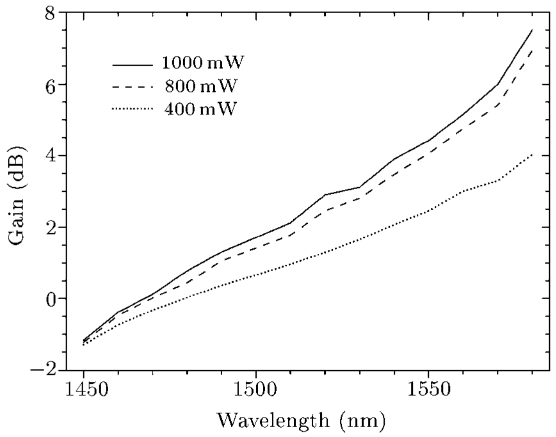

Fig. 3. Measured on–off gain versus wavelength with different pump powers.

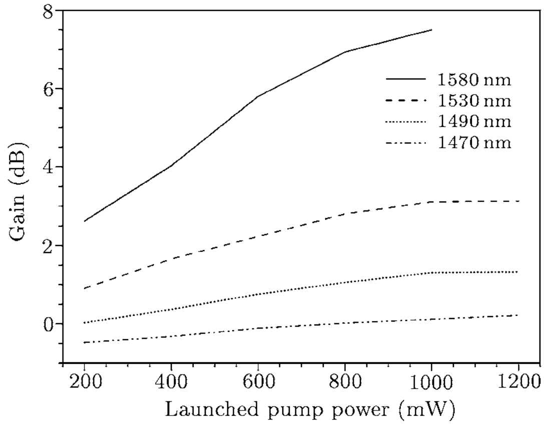

Fig. 4. Gain against launched pump power at different signal wavelengths.

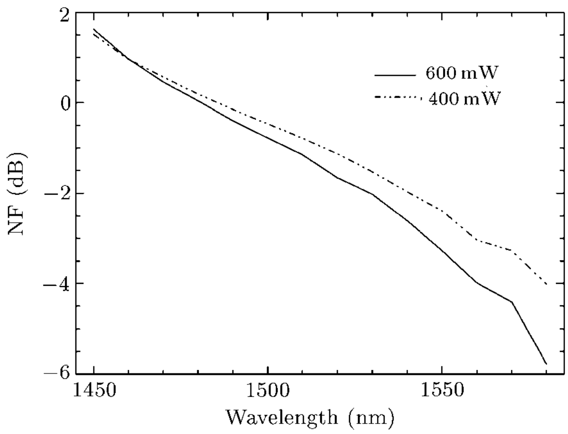

Fig. 5. Noise figure as a function of signal wavelength.

Figure 6 shows the effect of fibre length on the gain. It is clear that there exists an optimum fibre length for any given pump power. As the pump power increases, the available fibre gain and the optimum fibre length both increase. The optimized fibre length can be decided by precise theoretical models and careful experimental validation. The shortening of the thulium-doped fibre length is also a critical issue because of the high cost and background loss of the doped fibre.

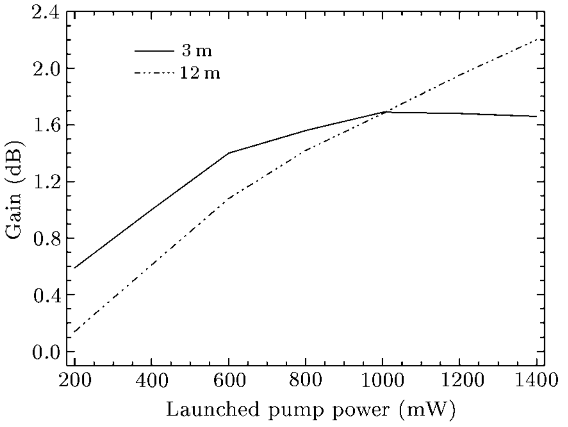

Fig. 6. Variation of the fibre gain with launched pump power and fibre length.

It is surprising that the TDSFA has an amplification capability not only in the *S* band, as a common TDFA does, but also in the *C* and *L* bands. We believe that the complex composition of the fibre affects the characteristics of the amplifier. Here the concentration of P_2O_5 is 3.44 mol% and that of Al_2O_3 is 10.10 mol% in the Tm-doped fibre. The presence of P and Al elements results in the fact that the amplifier gain appears in a longer wavelength region.[13] The co-doping of P and Al can increase the maximum concentration of the rare earths before the clustering occurs, and can widen the gain bandwidth of the amplifier. There are a few reasons accounting for the low gain. First, the pump wavelength is not the most effective one because of the weak absorption. Second, a strong pump-ESA depletes the upper-level population. Third, the absorption loss of the signal in the Tm-doped fibre is also significant. Further research is needed to improve the pumping efficiency.

We have successfully observed an inverted population between the $^3F_4$ and $^3H_4$ states in a Tm^{3+}-doped silica fibre by pumping at 1064 nm and have demonstrated a wide amplifier in the *S* and *C* bands. It has been shown experimentally that a bi-directional pumping is much more appropriate than a single end pumping in terms of gain and noise figure.

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