Ultra-short Wavelength Operation of Thulium-doped Fibre Amplifier in the 1628-1655nm Waveband

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Abstract *We present a silica-based thulium-doped fibre amplifier in the 1628-1655nm waveband based on Tm/Ge co-doped fibre. Up to 19dB external small signal gain and a noise figure of 4.4dB are achieved at 1655nm.*

Introduction

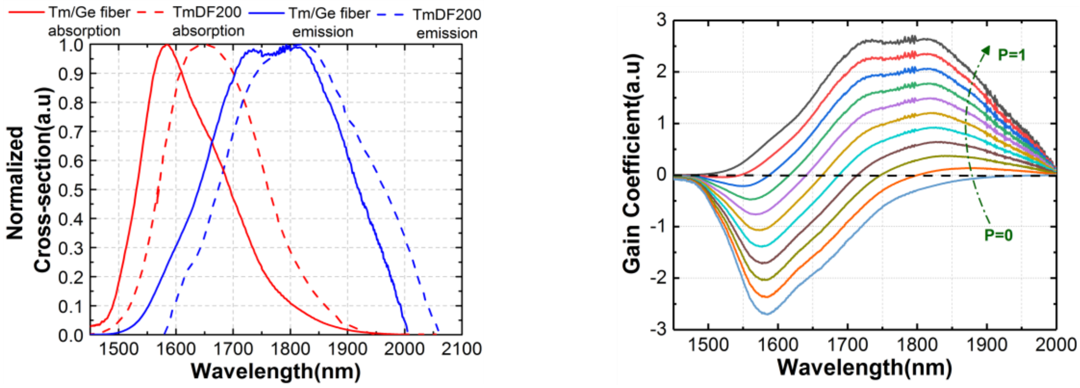
With the growing demand for capacity in optical fibre transmission, considerable research has been devoted to the 1.6-2 µm wavelength region as an emerging transmission window for next generation optical communications based on hollow-core photonic-bandgap fibres (HC-PBGFs) [1]. As the low loss window of silica fibre extends up to 1.7 µm, and with the continual improvement of background loss in HC-PBGFs, the possibility of future optical communications networks operating seamlessly from 1.55 to 2µm is emerging, requiring efficient optical fibre amplifiers covering the entire 1.55-2µm waveband.

To date, the L-band erbium doped fibre amplifier (EDFA) can only covers wavelength up to 1.62 µm, and various configuration of thulium-doped fibre amplifiers (TDFAs) have been demonstrated offering high gain and low noise performance across the wavelength 1700 – 2050 nm range[2,3]. With effective management of amplified spontaneous emission (ASE), the short-wavelength amplification edge of the TDFA has further extended down to 1650 nm with a small signal gain of 8dB demonstrated[4]. This is a great improvement but a ~30 nm spectral gap still exists between operating windows of the EDFA and TDFA.. Very recently, we have explored a new glass composition (particularly, a thulium (Tm) and germanium (Ge) co-doped silica fibre) and successfully demonstrated a tunable Tm-doped fibre laser in the wavelength range of 1620-1660 nm[5]. With the distinctive feature of blue-shifted absorption and emission spectra, the Tm/Ge co-doped fibre provides the intriguing possibility of bridging the gap between the long wavelength edge of the L-band EDFA and short wavelength edge of the TFDA.

In this paper, we experimentally demonstrate ultra-short wavelength operation of a TDFA and present the first realization of a silica-based TDFA operating down to as short as 1628 nm.

Fibre characterisation

The Tm/Ge-doped fibre was fabricated in-house using the conventional MCVD technique in conjuction with solution doping (dopant



(a)

(b)

Fig. 1(a) normalized absorption and emission cross-sections for Tm-doped fiber (OFS TmDF200) and in-house fabricated Tm/Ge co-doped fiber, respectively, and (b) the calculated normalized gain coefficient of Tm/Ge co-doped fiber.

concentration of ~0.004 mol% for Tm_2O_3 and ~19 mol% for GeO_2). The fibre has a core diameter of 4.4 μm and an NA of ~0.28. As compared to commercial Tm-doped aluminosilicate fibre (OFS TmDF200), the absorption spectrum of the Tm/Ge co-doped fibre is significantly blue shifted (70 nm shorter) as shown by the red solid line in Fig. 1(a) with a peak absorption of ~20 dB/m at 1580nm. According to the McCumber theory, the derived emission cross-section of Tm/Ge co-doped fibre is also blue-shifted by about 50 nm compared to TmDF200 fibre (blue solid line in Fig. 1(a)). Therefore, it is anticipated that the proposed Tm/Ge co-doped fibre can be used for efficient signal amplification at wavelengths much shorter than1650 nm.

Firstly, it is useful to compute the wavelength dependence of net gain as a function of population of the upper laser level (populaiton inversion). The net gain coefficient, G(λ), can be expressed by the following equation[6]:

$$G(\lambda) = N[p\sigma_e(\lambda) - (1-p)\sigma_e(\lambda)]$$

where p represents the population of the upper laser level, and N stands for the total number of Tm^{3+} ions. As shown in Fig. 1(b), the gain spectrum strongly depends on the population inversion and the gain peak shifts to shorter wavlenghts as the inversion level is iincreased. Therefore to achieve efficient signal amplification below 1700nm, more than 30 % population inversion is required necessitating optimization of the fibre length for a given pump wavelength.

Experiment setup

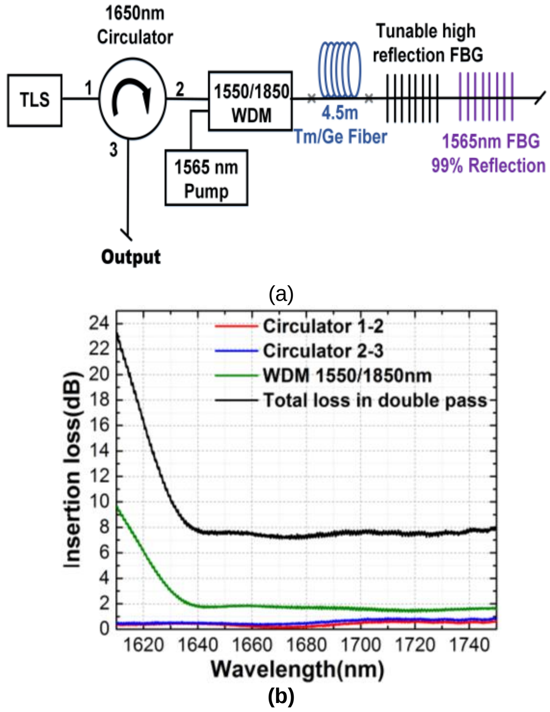


Fig. 2 (a) Schematic of the TDFA, TLS: tunable laser source; (b) insertion losses of the WDM coupler (green) and circulator (blue and pink) used in the setup, and the total optical loss of the double pass cavity.

Fig. 2(a) shows a schematic of the TDFA. In our experiment, a commercially available tunable laser source (Tunics T100S-HP) covering the wavelength range of 1500-1680 nm was used as a seed source with an input power of -20 dBm and 0 dBm for small and saturated signals, respectively. An optical circulator optimized at 1650 nm and with high optical isolation (>40 dB at center wavelength) and low insertion loss (0.45 dB) was employed as depicted in Fig. 2(b). In order to extract enough gain at short wavelengths, a high population inversion is required and an in-house built high-power Er/Yb fibre laser operating at 1565 nm was used as a pump source with a maximum output power of 4.35 W (36.3 dBm). A dielectric filter-based 1550/1850 nm wavelength division multiplexer (WDM) was used for combining the pump and signal. As shown in Fig. 2(b), the insertion loss of the WDM coupler was less than 2dB but this gradually increased at wavelengths shorter than 1640 nm. In addition, Fig. 2(b) also shows the total optical loss in a double pass configuration including the loss of an optical circulator, a 1550/1850nm WDM coupler as well as the optimized splicing loss of 0.8 dB between standard SMF and Tm/Ge co-doped fibres.

To realize short wavelength operation, a tunable fibre Bragg grating (FBG) was used in our experiment as an ASE filter as well as a narrowband signal retroreflector to realize a double pass implementation.

The FBG can be tuned from 1620 nm through to 1660 nm by using an axial compression mechanism. The measured reflectivity and bandwidth of the FBG varied from 91 % to 94 % and from 0.67 nm to 1 nm respectively, depending on the operating wavelengths. Moreover, a 1565 nm FBG with ~99% reflection was incorporated to recycle the residual pump light (~0.4 W). The external gain and NF of the amplifier was measured by an optical spectrum analyzer (Yokogawa AQ6375) and a thermal power meter (Ophir 3A-FS).

Result and discussion

Figure 3 shows the gain and noise figure (NF) performance of the proposed TDFA. An external small-signal gain of 19 dB was achieved at 1655nm, 8dB at 1632nm and 4dB at 1628nm. Compared to our previous demonstration of a short-band TDFA[3], we have successfully extended the short wavelength edge of the silica-based TDFA from 1650 nm to 1628 nm. The

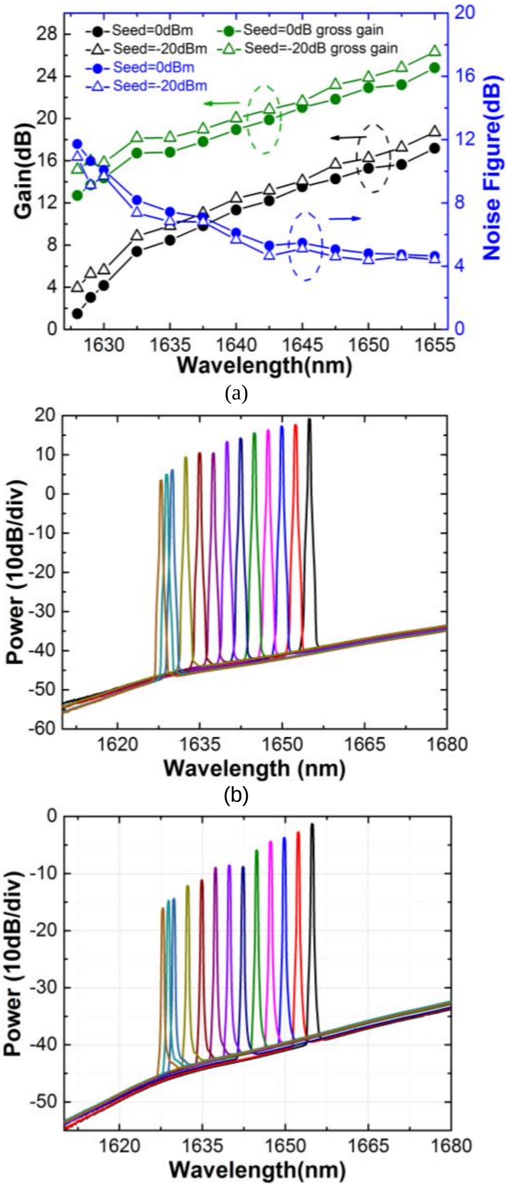


Fig. 3 (a) Gain and NF performances of the TDFA. Amplified spectra for (b) saturated and (c) small signals, measured with 0.5nm OSA resolution.

saturated gain shows similar behavior and varies from 7 dB to 17.2 dB with only 2.5 dB difference as compared to the small signal gain. The external NFs for saturated signal and small signal were as low as 4.6dB and 4.4dB at a wavelength of 1655nm but increased towards shorter wavelengths. This is mainly due to the high insertion loss of the WDM coupler and strong re-absorption of signal light by Tm ions in their ground state. By considering the total insertion loss of our amplifier with the double pass architecture, the gross (or internal) small-signal gain is around 15-26dB in the 1628-1665 nm. Therefore, further improvement in the performance of the TDFA is expected with higher pump powers (or indeed a different choice of pump wavelength such as 793nm, which has been theoretically investigated[7] with the conclusion that the gains at shorter wavelengths will be enhanced compared to 1550nm pumping), further optimization of both the passive fibre components and splicing loss between the active and passive fibres. Figures 3(b) and (c) show the amplified optical spectra for the saturated and small signal regime, respectively. The amplified small signal has 30–38dB in-band optical signal-to-noise ratio (OSNR) across the entire amplification band while the amplified saturated signal exhibits over 50 dB in-band OSNR.

Conclusions

With a new glass composition (i.e. Tm/Ge co-doped fibre), we have successfully blue-shifted the emission cross-section of TDF compared to conventional (aluminosilicate based) Tm-doped fibre. By constructing a double-pass amplifier, we have demonstrated a silica-based TDFA operating from 1628 nm to 1655 nm, a ~2THz gain bandwidth extension compared to the previous best report. Up to 19dB small signal gain (external) and a NF as low as 4.4 dB were achieved at 1655nm with >30dB in-band OSNR.

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