Improving broadband emission within Bi/Er doped silicate fibres with Yb co-doping

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Abstract: We present Bi/Er/Yb co-doped silicate fibre (BEYDF) which is fabricated by co-doping with Yb_2O_3 into Bi/Er doped silicate fibre (BEDF), and investigate its properties associated with Yb co-doping. Spectral absorption, emission, emission lifetime, ESA and gain characteristics of BEYDF are experimentally investigated and compared with those of BEDF to reveal particular impacts of Yb on the broadband spectral characteristics. We measured Yb^{3+} emissions at 980 nm and 1040 nm in BEYDF, and emissions related to Bi active centres (BACs, at 1100 nm and 1420 nm) and Er^{3+} (1530 nm) in BEYDF and BEDF under 830 nm pumping. Evidences of Yb^{3+}→BAC energy transfer process, in addition to the normal Yb^{3+}→Er^{3+} energy transfer process are noticed. Compared with BEDF, BEYDF has shown both broadened and enhanced emissions and gain. In particular, the overall emission bandwidth within a 4 dB intensity is attained over $\Delta\lambda$ = (1000–1590) nm in BEYDF, and just over $\Delta\lambda$ = (1250–1590) nm in BEDF. The overall emission intensity is enhanced by a factor of 2.5 in BEYDF over that of BEDF. Furthermore, Er^{3+} gain at 1530 nm is increased and BAC linked ESA at 1400 nm is reduced in BEYDF. Yb^{3+} related emissions and energy transfers from the excited Yb^{3+} to both the Er^{3+} and BACs can explain the improvements of emission and gain. These results indicate that Yb^{3+} co-doping can be used to expand and enhance broadband emissions and gain in BEYDFs.

OCIS codes: (160.2290) Fiber materials; (160.2540) Fluorescent and luminescent materials; (060.2270) Fiber characterization; (060.2300) Fiber measurements; (060.2400) Fiber properties.

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#242457 Received 5 Jun 2015; revised 4 Aug 2015; accepted 18 Aug 2015; published 2 Sep 2015

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1. Introduction

Wavelength division multiplexing (WDM) technology within high capacity telecommunication systems requires broadband lasers and amplifiers. Erbium (Er) doped fibres (EDFs) have been extensively developed as a component of such technology for laser and amplifier generation at λ_{em} ~1.5 μm region since their first demonstration in 1965 by Snitzer *et al.* [1]. Broadband emissions associated with bismuth (Bi) active centres, labelled herewith as BAC, at λ_{em} ~1.3 μm window promising for broadband applications were reported by Fujimoto *et al.* in 2001 [2]. Further work demonstrated lasing and amplification from λ_{em} ~1150 nm to λ_{em} ~1450 nm in Bi co-doped fibres (BDFs), which varied with composition including other co-dopants such as Al, Ge and P.

To extend the operating wavelength range of EDFs or BDFs, Bi/Er co-doped silicate fibres (BEDFs) have been fabricated with the National Fibre Facility at UNSW. BEDFs are potential gain materials for broadband applications in modern telecommunication systems. Broadband emissions have been achieved in BEDFs over λ_{em} ~1100 nm to λ_{em} ~1570 nm from the characteristic emissions of both Er^{3+} and BACs [3–6]. In addition, ON/OFF gain over g = + 2.4 dB/m has been observed in BEDFs, especially within λ_{em} ~1400 nm and λ_{em} ~1530 nm centred emission bands under λ_{ex} = 830 nm pumping [6]. However, the emissions and gain

#242457 Received 5 Jun 2015; revised 4 Aug 2015; accepted 18 Aug 2015; published 2 Sep 2015

obtained from BEDFs are not high nor uniform enough for practical use – largely due to the excited state absorption (ESA) and up-conversion (UC) processes associated with Er^{3+} and BAC [4,7]. ESA and UC processes can adversely affect emissions and gain via reducing the active pump absorption [8]. One possible way to improve the emissions and gain could be by co-doping BEDFs with another material, which is capable of transferring energy to both Er^{3+} and BAC.

We considered ytterbium ions (Yb^{3+}) as a good candidate for this purpose. Yb^{3+} is well known as an efficient emitter and sensitizer (i.e. energy transfer agent) with broad absorption band over $\Delta\lambda$ = (800–1080) nm and high absorption cross section (maximum at λ_{abs} ~980 nm) [9,10]. In particular, Yb^{3+} can absorb at λ_{abs} ~830 nm in the shorter wavelength tail of its absorption band centred on the $^2F_{5/2}$ energy level and emissions from Yb^{3+} in silica host have been reported under excitation at this end of the band (λ_{ex} = 840 nm) [11]. Moreover, Yb^{3+} can efficiently transfer energy to other ions, including Er^{3+} [9,12–14] and also to BAC [15,16].

Energy transfers between rare earths involve transitions outside the shielded intra-*f-f* transitions and are therefore necessarily sensitive to the host environment. Consequently, phosphate glasses are usually a preferred host over germanate for efficient energy transfer, of Yb^{3+} to heavily doped Er^{3+} (empirically determined to be optimized at ten times the concentration of Yb). The process is helped by the longer Yb^{3+} $^2F_{5/2}$ level lifetime (τ > 1 ms) in phosphate which dominates over the back energy transfer rate from Er^{3+} [13]. Although this value is more than ten times larger than that in germanate glass, Yb^{3+} has a comparable lifetime (τ > 0.8 ms) in silica hosts [10] which enables efficient energy transfer between $Yb^{3+}\rightarrow Er^{3+}$ [1,12,13]. Furthermore, energy transfer of $Yb^{3+}\rightarrow$BAC was reported in silica hosts and even in germanate hosts [15,16] – this provides an intriguing pathway for exploring more efficient energy transfer in more complex combinations to further expand the total emission band possible within defect rich fibres. Therefore, we co-doped Yb^{3+} into the silica-based BEDF and made a new type of active fibre – generically labelled Bi/Er/Yb co-doped silica-based fibre (BEYDF), aimed at improving the emission and gain characteristics by utilizing Yb^{3+} related emissions and potential energy transfer process.

This work experimentally investigates on spectral absorption, emission, emission lifetime, ESA and gain characteristics of BEYDF and compares to those of BEDF. The contribution of Yb related emissions and energy transfer process in broadening the wavelength range and enhancing the emission and gain in BEYDF under λ_{ex} = 830 nm pumping is explored.

2. BEYDFs and BEDF

Two BEYDFs and one BEDF have been fabricated for this study by MCVD and *in situ* solution doping [17]. The fibres have been drawn from preforms fabricated with identical soot recipes and processing conditions. The Si concentrations in these fibres are [Si] = (27~28) at% (defined to be the number of atoms in 100 that are silicon). One BEYDF (BEYDF1) and the BEDF (BEDF1) have been fabricated with similar concentrations of Bi and Er for comparison – the main distinction is the presence of Yb in BEYDF1, while there is no Yb in BEDF1. The other BEYDF (BEYDF2) has been fabricated with lower concentrations of both Bi and Er. These fibres are used to extract the spectral characteristics of Yb^{3+} in the BEYDF. Germanium (Ge) has been used to control the core index; however, we know that it will likely play a central role in aggregating defect sites despite being much less than the silicon content. To achieve the desired value for the core index, [Ge] = (0.92~1.25) at% has been used. The material compositions in the fibre core are estimated using energy dispersive X-ray (EDX) analysis and are summarised in Table 1. For simplicity all concentrations are given in at%.

#242457 Received 5 Jun 2015; revised 4 Aug 2015; accepted 18 Aug 2015; published 2 Sep 2015

Table 1. Approximate concentrations of dopants in the BEYDFs and BEDF.

Label	Fibre Type	Bi	Er	Yb	Al	Ge
		at%	at%	at%	at%	at%
BEDF1	BEDF	0.07	0.10	0	0.30	1.25
BEYDF1	BEYDF	0.07	0.10	0.04	0.30	1.18
BEYDF2	BEYDF	0.04	0.04	0.03	0.30	0.92

3. Experimental results and analysis of BEYDFs and BEDF

Spectral properties of Yb^{3+} are extracted by measuring the absorption and emissions in the BEYDFs and BEDF, described in section 3.1. Energy transfer from the Yb^{3+} elsewhere in the BEYDFs are explored and inferred from the measurements of the $^2F_{5/2}$ level emission lifetime in section 3.2. From this data, the impact of Yb^{3+} co-doping on broadband spectral emission and gain properties are discussed in sections 3.3 and 3.4.

3.1 Spectral properties of Yb^{3+} (absorption and emission)

Spectral absorptions (α) are characterized in the BEYDFs (BEYDF1, BEYDF2) and BEDF (BEDF1) by cut-back method and shown in Fig. 1(a). The fibres produce absorptions mainly at λ_{abs} ~800 nm, 1400 nm and 1530 nm bands. The absorption band located at λ_{abs} ~800 nm is actually composed of two individual absorption bands: at λ ~800 nm and λ ~830 nm, as shown at the inset of Fig. 1(a). Often the unidentified Bi defect centre is termed BAC in the literature which presupposes that Bi is playing an active role in forming a new transition, although whether the role is active or passive is unclear. Here, we can use the term BAC bearing in mind its qualification.

Absorption at λ_{abs} ~800 nm is attributed to Er^{3+} (Er^{3+}: $^4I_{15/2} \rightarrow {}^4I_{9/2}$ electronic transition), and that at λ_{abs} ~830 nm to a BAC linked to silica (BAC-Si) [18], although we obviously cannot rule out a germanate or a germanate-silica analog [19]. Absorption at λ_{abs} ~1530 nm is the well-known intra $^4I_{15/2} \rightarrow {}^4I_{13/2}$ transition absorption of Er^{3+}. A broad absorption band at λ_{abs} ~1050 nm is also observed in both BEYDF1 and BEDF1. The measured absorption at λ_{abs} ~1050 nm is comparable with the absorption around this region produced from BAC linked to Al (BAC-Al), as reported in BEDFs and BDFs [7,19].

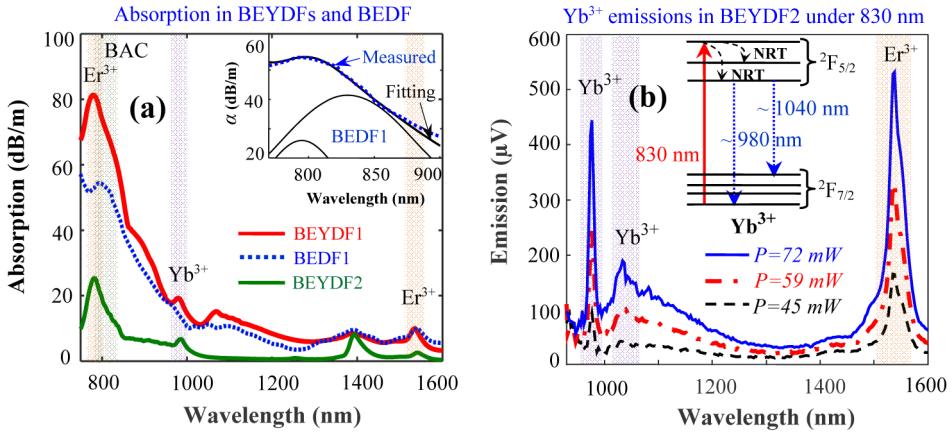

Fig. 1. (a) Absorption in the BEYDFs and a reference BEDF (inset: absorption at around λ_{abs} ~800 nm fitted with two Gaussian functions at λ = 800 nm and λ = 830 nm, shown for BEDF1). (b) Yb^{3+} related emissions in BEYDF2 under λ_{ex} = 830 nm pumping (inset: energy levels corresponding to the observed Yb^{3+} emissions under λ_{ex} = 830 nm pump excitation; NRT: non-radiative transitions).

#242457 Received 5 Jun 2015; revised 4 Aug 2015; accepted 18 Aug 2015; published 2 Sep 2015

Absorption of Yb^{3+} (λ_{abs} ~980 nm): Yb^{3+} has a typical absorption band at λ_{abs} ~980 nm corresponding with the intra-band transition $^2F_{7/2} \rightarrow {}^2F_{5/2}$ [9,10]. Furthermore, absorption at λ_{abs} ~980 nm can also be produced from Er^{3+} via the $^4I_{15/2} \rightarrow {}^4I_{11/2}$ intra-band transition. Here, it is observed that the λ_{abs} ~980 nm absorptions are noticeably raised in BEYDF1 and BEYDF2, which are co-doped with Yb^{3+}. Furthermore, BEDF1 has Er^{3+} absorption at λ_{abs} ~1530 nm similar to that of BEYDF1. However, BEDF1 (with no Yb^{3+} co-doping) does not produce comparable absorption at λ_{abs} ~980 nm. Therefore, the measured absorption bands at λ_{abs}~980 nm in both the BEYDFs can be attributed to the Yb^{3+} alone.

To identify the characteristic emissions of Yb^{3+} in BEYDFs, emissions are measured first in BEYDF2, which is doped with lower concentrations of both Bi and Er (Table 1). Hence, the emissions of Yb^{3+} are more distinguishable in BEYDF2. BEYDF2 exhibits considerable absorption at λ_{abs} ~830 nm (α ~12 dB/m). Hence, an 830 nm laser diode has been used to excite BEYDF2 to measure its spectral emissions. The emissions are measured using a forward detection setup comprising of a monochromator and lock-in amplifier, similar to that reported earlier [20]. The output power from the fibre ends is recorded using an optical power meter (PM). The emissions in BEYDF2 using a length of L ~10 cm measured over $\Delta\lambda$ = (900–1600) nm range are shown in Fig. 1(b). It is observed that BEYDF2 produces emission mainly at λ_{em} ~980 nm, 1040 nm and 1530 nm bands under λ_{ex} = 830 nm pump excitation. Emissions at λ_{em} ~1530 nm originate from the Er^{3+} intra-band $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition. Emission characteristics in BEYDF2 are described below in more detail.

Emissions of Yb^{3+} (λ_{em} ~980 nm and 1040 nm): Yb^{3+} ions generally produce one emission band at λ_{em} ~980 nm and another one at λ_{em} ~1040 nm, arising from the intra-band $^2F_{5/2} \rightarrow {}^2F_{7/2}$ transitions [10,11]. Yb^{3+} has a broad absorption band between $\Delta\lambda$ ~(800–1080) nm with a large absorption cross section of σ_{abs} ~2×10^{-26} m^2 at λ_{abs} ~830 nm in silica hosts [9–11]. Emissions from Yb^{3+} at λ_{em} ~980 nm and 1040 nm bands under λ_{ex} = 840 nm pump excitation have been reported in an Yb^{3+} doped silica fibre [11].

When BEYDF2 is pumped at λ_{ex} = 830 nm, emissions at λ_{em} ~980 nm and 1040 nm are observed, similar to the characteristic emissions of Yb^{3+} with excitation at λ_{ex} = 840 nm [10,11]. It is observed that the intensity of Yb^{3+} emission at λ_{em} ~980 nm is comparable to that of Er^{3+} emission at λ_{em} ~1530 nm in BEYDF2. When pumped at λ_{ex} = 830 nm, Yb^{3+} is excited to the upper Stark line of the $^2F_{5/2}$ level. They drop down to the lower Stark line of the $^2F_{5/2}$ level by non-radiative transitions (NRT). Yb^{3+} at the $^2F_{5/2}$ level transfers energy to the $^2F_{7/2}$ level producing emissions at λ_{em} ~980 nm and 1040 nm. The inset of Fig. 1(b) presents the energy levels corresponding to the observed emissions of Yb^{3+} at λ_{em} ~980 nm and 1040 nm.

The λ_{em} = 980 nm emission from Yb^{3+} in the BEYDF is significant since it can act as a pump for exciting both the Er^{3+} and BAC, producing their own distinctive emissions.

Emissions of BAC (λ_{em} ~1420 nm and 1100 nm): BEYDF2 produces emissions at λ_{em} ~1420 nm under λ_{ex} = 830 nm pump (Fig. 1(b)). The 1420 nm emission is similar to the emission of Bi active centre linked to Si (BAC-Si) reported in BDFs [18]. Another emission at λ_{em} ~1100 nm combined with the Yb^{3+} related emission at λ_{em} ~1040 nm is also observed in BEYDF2. This 1100 nm emission is comparable to those emissions attributed to BAC-Al reported in Al-doped BEDFs and BDFs [7,21].

Hence, Yb^{3+} related spectral absorption at λ_{abs} ~980 nm, and emissions at λ_{em} ~980 nm and λ_{em} ~1040 nm are identified in the BEYDF.

3.2 Energy transfer from Yb^{3+} to Er^{3+} and BAC

Energy transfer process generally reduces the intra-band emission lifetime (or lifetimes) of donor ions (or active centres); this process increases the effective lifetime of acceptor ions or defects. Therefore, lifetimes in the BEYDF and BEDF are measured to identify indirectly energy transfer process linked to Yb^{3+}. To measure the lifetimes, the BEDF and BEYDFs

#242457 Received 5 Jun 2015; revised 4 Aug 2015; accepted 18 Aug 2015; published 2 Sep 2015

were excited with a λ_{ex} = 808 nm pumping, which produces emissions in these fibres comparable to those under λ_{ex} = 830 nm pumping.

Reduced lifetime of Yb^{3+}: An upper state lifetime of Yb^{3+} was reported to be τ ~840 µs in silica doped fibres [10]. The inset of Fig. 2(a) shows the emission decay curves measured at λ_{em} ~980 nm in BEYDF1 and BEYDF2. It has been noticed that, signal at λ_{em} ~980 nm is not significant in BEDF1 where there is no Yb^{3+} co-doping. The lifetimes of Yb^{3+} emissions at λ_{em} ~980 nm are measured to be τ ~490 µs and 400 µs in BEYDF1 and BEYDF2, respectively. These values are much lower than the typical lifetime (τ ~840 µs) of Yb^{3+} in silica fibres [10]. The reduced lifetimes indicate the possibility of energy transfer from Yb^{3+} ion to other active centres (such as to Er^{3+}, BAC) in BEYDFs.

Yb^{3+} to Er^{3+} energy transfer: Energy transfer from Yb^{3+} to Er^{3+} is a well-known process [9,12–14]. Figure 2(a) presents the emission decay curves measured at λ_{em} ~1530 nm in BEYDFs and BEDF. It is observed that the emissions at this wavelength decay slowly in both the BEYDFs compared to that in the BEDF. The emission band of BAC-Si at λ_{em} ~1420 nm overlaps the emission band of Er^{3+} at λ_{em} ~1530 nm in these fibres. It is assumed the emission decay curve at λ_{em} ~1530 nm includes the contribution from emission at λ_{em} ~1420 nm attributed to BAC-Si. All the three fibres have equal lifetimes: τ ~640 µs of BAC-Si at λ_{em} ~1420 nm. The lifetimes of the BAC-Si measured in these fibres correspond well with the reported lifetime (τ ~600 µs) of BAC-Si in BDFs [18]. Taking into account the effect of BAC-Si lifetime, Er^{3+} lifetimes at λ_{em} ~1530 nm have been evaluated by fitting the emission decay curves using exponential functions. Thus, the lifetime of Er^{3+} is estimated to be τ ~6 ms in BEDF1, although it is found to be longer in both the BEYDFs. For instance, the measured lifetimes of Er^{3+} are τ ~7.2 ms and 7.9 ms in BEYDF1 and BEYDF2, respectively. In particular, BEYDF1 and BEDF1 have similar concentrations of Er and Bi (Table 1), and the main difference is the difference in Ge and the presence of Yb^{3+} in BEYDF1. The longer lifetime of Er^{3+} at λ_{em} ~1530 nm in BEYDF1, could be linked to the presence of Yb^{3+}, resulting in the normal $Yb^{3+} \rightarrow Er^{3+}$ energy transfer process. A similar process is responsible for the reduced lifetime of Yb^{3+} and longer lifetime of Er^{3+} measured in BEYDF2.

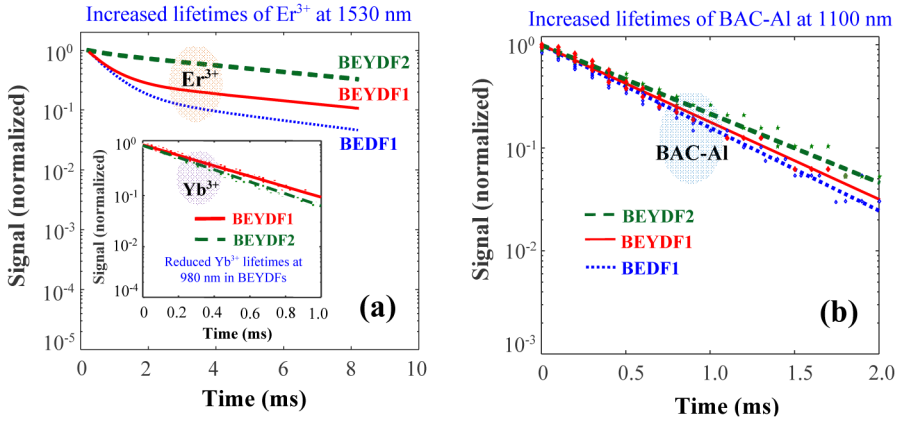

Fig. 2. Increased lifetimes of Er^{3+} and BAC in BEYDFs due to the energy transfer from Yb^{3+} to Er^{3+} and BAC: (a) Increased lifetimes of Er^{3+} at λ_{em} ~1530 nm in BEYDFs (inset: reduced lifetimes of Yb^{3+} at λ_{em} ~980 nm in BEYDFs). (b) Increased lifetimes of BAC-Al at λ_{em} ~1100 nm in BEYDFs.

Yb^{3+} to BAC (BAC-Al) energy transfer: Emission lifetime of BAC was shown to increase due to energy transfer process from Yb^{3+} to BAC reported in Bi and Yb doped glasses [14]. The emission decay curves of BAC-Al at λ_{em} ~1100 nm in BEYDFs and BEDF are given in Fig. 2(b). It shows that the lifetimes of BAC-Al at λ_{em} ~1100 nm are longer in the BEYDFs (τ ~580 µs and 650 µs) than that in the BEDF (τ ~540 µs). Both of the measured lifetimes are

#242457 Received 5 Jun 2015; revised 4 Aug 2015; accepted 18 Aug 2015; published 2 Sep 2015

close to the typical lifetime (τ ~630 µs) of BAC at λ_{em} = 1140 nm, reported in Bi and Al doped silicate glasses [2]. Since BEYDF1 and BEDF1 have similar concentrations of Bi and Al (Table 1), similar amount of BAC-Al are likely to form in these fibres. Therefore, the longer lifetime of BAC-Al in BEYDF1 could originate from Yb^{3+}→BAC-Al energy transfer process.

It is noticed that the lifetime of BAC in BEYDF2 increased more than that in BEYDF1, which indicates a stronger ET process in BEYDF2. Compared with BEYDF1, the higher concentration ratio of [Yb]:[Bi] in BEYDF2 can introduce stronger ET from Yb^{3+} to BAC [13]. As a consequence, Yb^{3+} lifetime is more reduced and BAC-Al lifetime is further increased in BEYDF2.

Therefore, energy transfers from Yb^{3+} to both the Er^{3+} and BAC are realized in BEYDFs. Yb^{3+} related emissions and energy transfer processes have significant impacts on the broadband spectral characteristics, which is explored next.

3.3 Impacts of Yb^{3+} co-doping on emissions

To find the effects of Yb^{3+} co-doping on the emission of BEYDF, spectral emissions are measured and compared in BEYDF1 and BEDF1, which have been doped with similar concentrations of Bi and Er (from EDX and absorption).

Measurement system: Emissions in BEYDF1 and BEDF1 are measured using the experimental setup shown in Fig. 3(a). An 830 nm pigtailed laser diode is connected to the fibre under test (FUT) through a WDM (810/1310). Emissions are detected in the backward direction by an Agilent 86143B spectrum analyser (OSA: noise floor –45 dBm, resolution = 5 nm). Emissions recorded from the OSA are corrected for the spectral characteristics of the WDM. The emissions of BEYDF1 and BEDF1 are measured using fibre lengths L ~75 cm each under λ_{ex} = 830 nm up to P ~70 mW. The emissions of BEYDF1 and BEDF1 at the same input power of P ~40 mW are given in Fig. 3(b) for comparison.

The overall emissions are broad in these fibres, particularly those in BEYDF1. The fibres produce significant emissions from Er^{3+} at λ_{em} ~1530 nm and from BAC-Si at λ_{em} ~1420 nm. In addition, emissions of BAC-Al around λ_{em} ~1100 nm are also noticeable in BEYDF1 and BEDF1. The improved broadband emission characteristics in BEYDF1 are described below.

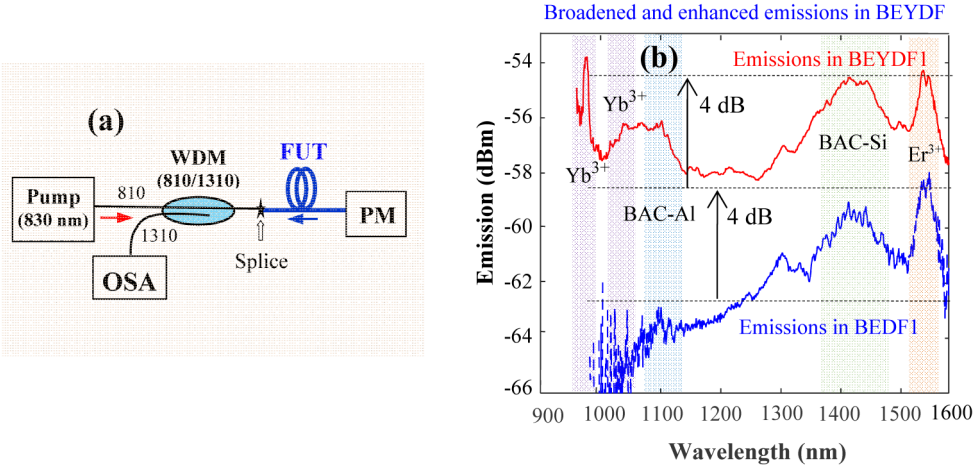

Fig. 3. (a) Experimental setup used to measure emissions in BEYDF and BEDF. (b) Broadened and enhanced emissions in BEYDF1 compared with those of BEDF1 measured at P ~40 mW under λ_{ex} = 830 nm pumping.

***Extended broadband emissions*:** Compared with BEDF1, BEYDF1 produces broader emissions under λ_{ex} = 830 nm pumping. For instance, the observed emission bandwidth within

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a 4 dB intensity increase is over $\Delta\lambda$ = (1000–1590) nm in BEYDF1, and just over $\Delta\lambda$ = (1250–1590) nm in BEDF1. We observed that Yb^{3+} produces emissions at λ_{em} ~1040 nm and 980 nm in BEYDF under λ_{ex} = 830 nm pump (Fig. 1(b)). The emission of Yb^{3+} at λ_{em} ~1040 nm combines with the emission of BAC-Al at λ_{em} ~1100 nm and creates a broad emission around this wavelength in BEYDF1. Moreover, BAC-Al can be excited by Yb^{3+} emission at λ_{em} ~980 nm to produce BAC-Al emission at λ_{em} ~1100 nm. For instance, significant emission from BAC-Al at λ_{em} ~1150 nm has been reported under λ_{ex} = 980 nm pump in BEDFs [3]. Therefore, Yb^{3+} to BAC energy transfer (corresponding to the 980 nm energy level) may enhance the emissions of a centre such as BAC-Al.

Thus, the overall emission wavelength range is broadened in BEYDF by Yb^{3+} emission and energy transfer.

Enhanced broadband emissions: The overall emission intensity is observed much stronger in BEYDF1 than that in BEDF1 (Fig. 3(b)). For instance, the overall emission intensity is enhanced over 2.5 times in BEYDF1 compared to that in BEDF1 measured at P ~40 mW under 830 nm pumping. Under λ_{ex} = 830 nm pumping, Yb^{3+} absorbs pump energy and emits at λ_{em} ~1040 nm and 980 nm. Yb^{3+} emission at λ_{em} ~1040 nm directly complements emissions associated with Er^{3+} and BAC in BEYDF1. Furthermore, Yb^{3+} emission at 980 nm can excite both Er^{3+} and BAC (BAC-Al), resulting in the enhancement of emissions linked to these active centres. As a consequence of all these effects, the overall emission intensity is enhanced in BEYDF1 in comparison to that of BEDF1.

Hence, both the emission bandwidth and intensity are improved in BEYDF than those of BEDF. Yb^{3+} related emissions and energy transfers from Yb^{3+} to Er^{3+} and BAC have significantly contributed to the observed improvements. Similar effects from Yb^{3+} co-doping are expected to be reflected on gain properties as explored next.

3.4 Impacts of Yb^{3+} co-doping on gain and ESA

ON/OFF gain and ESA (excited state absorption) are measured in BEYDFs and BEDF under 830 nm pumping using a configuration similar to that reported earlier [7,22]. Figure 4(a) presents the experimental results of ON/OFF gain and ESA in the BEYDFs and BEDF measured over $\Delta\lambda$ = (1300–1600) nm.

Reduced Bi ESA: Broad signal ESA over $\Delta\lambda$ = (800–1700) nm was reported in Bi and Al co-doped fibres with λ_{ex} = 1058 nm pumping [23]. In addition, signal ESA over $\Delta\lambda$ = (920–1500) nm in several BEDFs has been reported recently and the bandwidth and intensity of the ESA has also been found to be associated with BAC-Al [7].

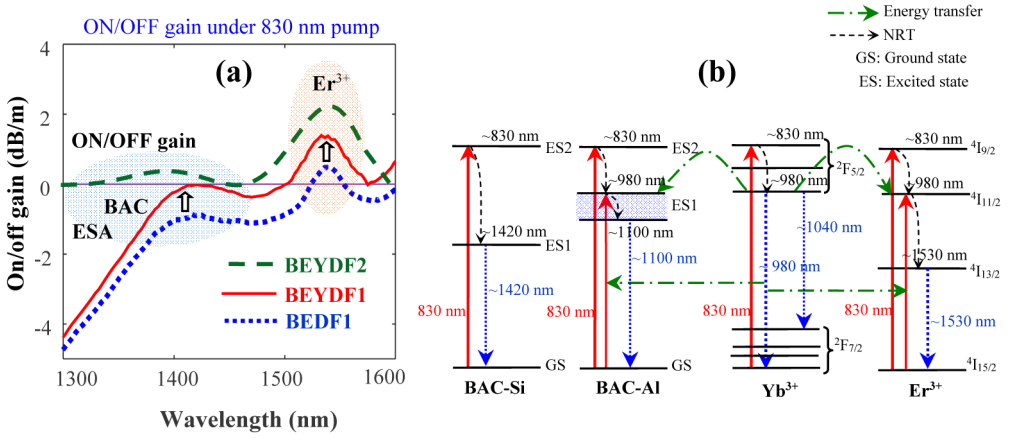

Fig. 4. (a) Increased ON/OFF gain at λ_{em} ~1530 nm and reduced ESA at λ_{em} ~1400 nm in BEYDFs compared with those of BEDF under λ_{ex} = 830 nm pumping. (b) Energy level diagram in BEYDFs showing the energy transfer processes from Yb^{3+} to Er^{3+} and BAC.

#242457 Received 5 Jun 2015; revised 4 Aug 2015; accepted 18 Aug 2015; published 2 Sep 2015

Figure 4(a) shows that BEYDF1 and BEDF1 produce broad signal ESA bands: over $\Delta\lambda$ = (1300−1500) nm in BEYDF1 and over $\Delta\lambda$ = (1300−1520) nm in BEDF1 under λ_{ex} = 830 nm pumping. It is observed that the bandwidth of the signal ESA (particularly that around λ_{em} = 1400 nm) is comparatively reduced in BEYDF1 than that of BEDF1. However, signal ESA in the measured wavelength range is not significant in BEYDF2, which is doped with low concentration of Bi. The signal ESA detected in BEYDF1 and BEDF1 can be linked to Bi (BAC-Al) [7,23], although we note the differences in Ge concentrations may also play a role. A number of recent works reported Bi active centre linked to Ge (i.e. BAC-Ge) to be a distinct active centre with the characteristic emissions at λ_{em} ~925 nm and 1650 nm [18,24,25]. In our case of BEDFs and BEYDFs, where Ge is used to control the core index, we have observed a small amount of emission at λ_{em} ~1650 nm in the fibre which is evidently related to the BAC-Ge. Since we are concerned mainly with the emission characteristics of the BEDF and BEYDFs over (1000−1600) nm range, the BAC-Ge is not of our main concern here.

Enhanced Er^{3+} ON/OFF gain: Er^{3+} produces ON/OFF gain at λ_{em} ~1530 nm in BEYDFs and BEDF under λ_{ex} = 830 nm pumping. The gains are superimposed upon the broad signal ESA in BEYDF1 and BEDF1. The ON/OFF gains at λ_{em} ~1530 nm are higher in both the BEYDFs (BEYDF1 and BEYDF2) than that of the BEDF (BEDF1). Since the BEDYF1 and BEDF1 have similar concentrations of Er (Table 1), the higher ON/OFF gain from Er^{3+} in BEYDF1 compared with that in BEDF1 can be explained by the normal $Yb^{3+}\rightarrow Er^{3+}$ energy transfer process, as described in section 3.2. Yb^{3+} at 980 nm can transfer energy to Er^{3+} at $^4I_{11/2}$ energy level, which can enhance emission and gain at λ_{em} ~1530 nm.

It is noticed that BEYDF2, doped with lower concentrations of both the Bi and Er, shows a higher gain at λ_{em} ~1530 nm than other fibres. The signal ESA should be reduced in BEYDF2, mainly due to the lower concentration of Bi. Moreover, due to the higher concentration ratio of [Yb]:[Er], stronger ET process ($Yb^{3+}\rightarrow Er^{3+}$) is expected in BEYDF2, resulting in the higher Er^{3+} gain at λ_{em} ~1530 nm [13]. The energy level diagram in Fig. 4(b) shows the energy transfer processes in BEYDFs.

Hence, in comparison to those in BEDF, the increase in gain at λ_{em} ~1530 nm and reduction in overall ESA around λ_{em} ~1400 nm are observed in BEYDF, which is helped by Yb^{3+} related emissions and energy transfer processes. These results suggest that it is a promising proposition to use Yb^{3+} co-doping to improve emissions and gain for broadband applications. In this regard, this work points to future research and development work similar to existing work in rare earth co-doped fibres involving energy transfer. For example, optimizing compositions of BAC, Er^{3+} and Yb^{3+} could be carried out with the aim to optimize broadband emission and gain using efficient energy transfer and improved pump absorption.

4. Conclusion

In summary, we have developed and tested a new type of active fibre – Bi/Er/Yb co-doped silicate fibre (BEYDF), which was made by co-doping with Yb^{3+} into Bi/Er doped silicate fibre (BEDF). Particular impacts of Yb^{3+} co-doping on enhancing the emission intensity and broadening the emission wavelength range of BEDF based on existing work using Yb^{3+} with Er^{3+} were experimentally demonstrated by carrying out an investigation and analysis of various important spectral properties such as absorption, emission, emission lifetime, ESA and gain and comparing these between the BEYDF and BEDF. We observed that the emission was broadened and enhanced in BEYDF over that within BEDF. In particular, the overall emission bandwidth for a 4 dB intensity increase was achieved over $\Delta\lambda$ = (1000−1590) nm in BEYDF and just over $\Delta\lambda$ = (1250−1590) nm in BEDF under 830 nm pumping. Moreover, the intensities of emission and gain were enhanced in BEYDF. For instance, the overall emission intensity in BEYDF was enhanced 2.5 times that of BEDF. Furthermore, the gain linked to Er^{3+} at 1530 nm was increased and the ESA linked to BAC at

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1400 nm was reduced in BEYDF. Yb^{3+} emissions (centred at λ_{em} ~980 nm and λ_{em} ~1040 nm) and energy transfer processes ($Yb^{3+} \rightarrow Er^{3+}$ and $Yb^{3+} \rightarrow$BAC) are considered to be behind such improvements of emission and apparent gain. Co-doping with Yb can therefore be used to increase the bandwidth of ultra-broadband emission of optical fibres and potentially enhance the use of these fibres in amplifier applications by expanding the accessible gain across this bandwidth.

Acknowledgment

Authors are thankful for the support by State Key Laboratory of Advanced Optical Communication Systems Networks, China, Natural Science Foundation of China (61377096 and 61405014), the ECR/FRP grant from the Faculty of Engineering UNSW and Heilongjiang young researcher support (1253G018). Authors are also thankful to Australian Research Council (ARC) for supporting the National Fibre Facility at the University of New South Wales.

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