# An all-fiber type $Er^{3+}/Yb^{3+}$ co-doped fiber laser

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In this paper, a distributed Bragg reflection (DBR) type $Er^{3+}/Yb^{3+}$ co-doped fiber laser of high output power and high slope efficiency was developed. Its gain medium was a 4.45-m-long $Er^{3+}/Yb^{3+}$ co-doped fiber. When it was pumped by a 1064-nm Nd:YAG, the linewidth of output laser was measured as 0.072 nm by 3 dB and 0.192 nm by 25 dB at 1552.08 nm. The maximum output power was measured as 69 mW. Its power stability was $< 5\%$, side mode suppression ratio was 59 dB, and the output wavelength stability was $\pm 0.01$ nm. The laser had a threshold of 12 mW and a slope efficiency of 22%.

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Rare-earth-doped fiber lasers that are capable of being broad wavelength tuned and narrow-linewidth, are finding application in the fields of optical communications, interferometry and spectroscopy. With their various advantages, these devices will be attached even greater importance in the future.

At present, the $Er^{3+}$-doped germanosilicate grating-based fiber lasers relied on the ready availability of conventional erbium-doped fibers, being developed, can provide preferable output signal and very broad tuning range. While these lasers showed excellent characteristics in many respects, the need for amplification in order to boost the low laser powers to useful levels of several mW or more is a drawback that prevents them from fully living up to the promise of a high performance low noise source[1]. We can enhance the pump absorption and the output laser powers by increasing the erbium doping concentration. However, at the same time, one problem will be brought about.

Sanchez found the $Er^{3+}$ ion concentration cannot be increased as high as possible as Ge-doped core fibers are quite prone to ion clustering[2,3], which not only leads to a degradation in the efficiency, but also gives rise to self-pulsing in the lasers. As a result, noises can be increased[4]. Therefore, the relatively low $Er^{3+}$ ion doping concentration, which limits the gain coefficient of $Er^{3+}$-doped fibers, is inevitable to sustain stable laser operation. In order to solve the problem, researchers tried various methods. One of the easy and effective ways to suppress the ion-pairs induced self-pulsing[5] in the lasers is co-doped $Yb^{3+}$ with $Er^{3+}$ in fibers. The $Yb^{3+}$ ions, having large peak absorption cross-section, can provide a highly efficient means of indirect pumping for $Er^{3+}$ ions[6]. So, we can decrease the $Er^{3+}$ ion doping concentration owing to the strong sensitization of $Yb^{3+}$ ions in the $Er^{3+}$-doped fibers. Thus, the ion-pair induced self-pulsing in $Er^{3+}$-doped fiber lasers can be effectively suppressed. Meanwhile, much higher pump absorption efficiency will be achieved.

$Er^{3+}/Yb^{3+}$ co-doped fibers are ideal gain medium for constructing fiber lasers. Their broad absorption band, which ranges from 800 to 1100 nm, and the two orders of magnitude higher pump power absorption[7] (compared with $Er^{3+}$-doped fiber) enable high efficient single frequency operation of fiber lasers. High output power can be achieved by using $Er^{3+}/Yb^{3+}$ co-doped fibers.

The energy levels, energy transfer and the propagation-rate equations of Er/Yb system are presented in Refs. [8 – 11].

Figure 1 shows the experimental setup. The resonant-cavity of the $Er^{3+}/Yb^{3+}$ co-doped fiber laser consists of $FBG_1$, $FBG_2$ and the $Er^{3+}/Yb^{3+}$ co-doped fibers.

The 1064-nm Nd:YAG pump had its stability $< 5\%$ (within 4 hours) and radiation angle $< 1.2$ mrad. The 1064-nm pumping light, with 400-mW maximum output power, was launched into a 4.45-m-long $Er^{3+}/Yb^{3+}$ co-doped fiber via a 1064/1550 nm wavelength division multiplexer (WDM) (additional loss versus wavelength shown in Fig. 2) and $FBG_1$ after coupling. The WDM adopted was to lessen the back reflection, and meanwhile, to enhance the stability of the fiber laser. The stimulated emission light generated in the fiber got through the narrowband $FGB_2$ and formed the expected output laser. To prevent back reflection, an isolator (isolation $> 50$ dB, return loss $> 60$ dB, insertion loss: 0.38 dB, bandwidth $> 40$ nm) was spliced to the end of $FBG_2$ and used as the output port. The FBGs

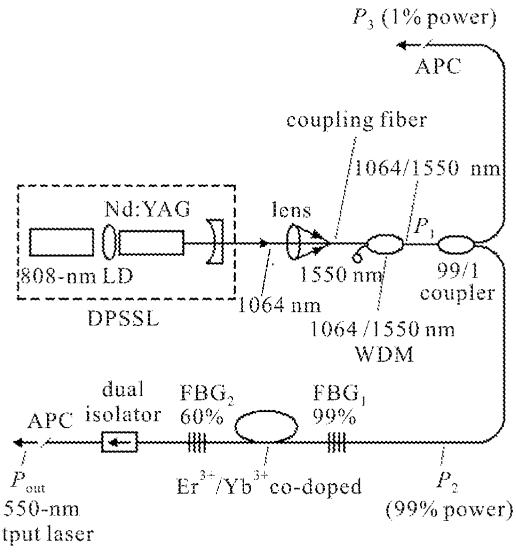


Fig. 1. Schematic configuration of the DBR $Er^{3+}/Yb^{3+}$ co-doped fiber laser.

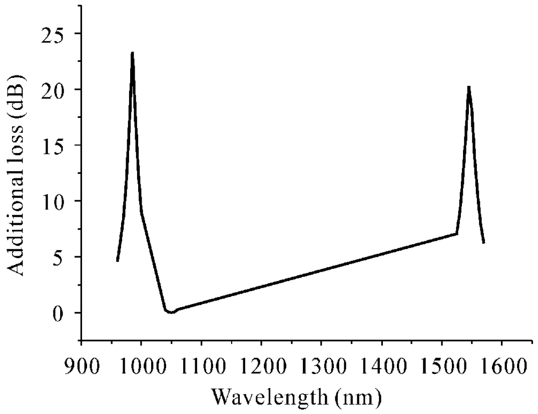
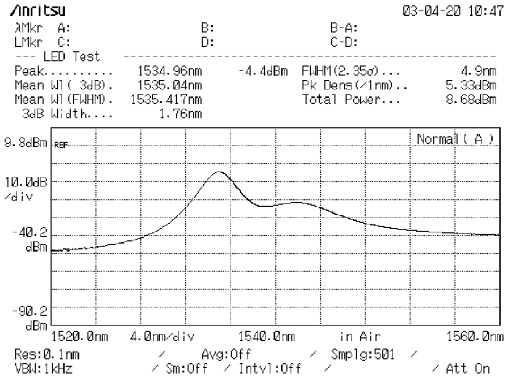


Fig. 2. Additional loss of the WDM versus wavelength.



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λMkr  A:                  B:               B-A:
LMkr  C:                  D:               C-D:
--- LED Test   -------------------------------------------------
Peak.........    1534.96nm   -4.4dBm  FWHM(2.35σ)...       4.9nm
Mean Wl( 3dB).   1535.04nm            Pk Dens(/1nm)..    5.33dBm
Mean Wl(FWHM).  1535.417nm            Total Power...     8.68dBm
 3dB Width....      1.76nm
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Res:0.1nm          /    Avg:Off          /  Smplg:501  /
VBW:1kHz           / Sm:Off  / Intvl:Off   /              / Att On
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Fig. 3. Superfluorescent spectrum.

were fabricated by an UV-excimer laser at 248 nm on the fiber. The $FBG_1$ has a high reflectivity of 99% which reduces the laser cavity parasitic loss.

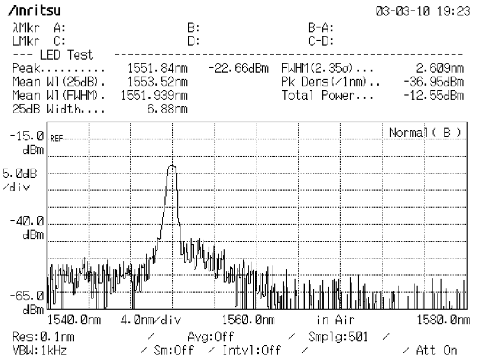
The output coupling $FBG_2$ has a 60% reflectivity optimized for the high output power of the fiber laser, which has a narrow bandwidth to provide sufficient lasing mode selection. And the two FBGs have same central reflected wavelength. The numerical aperture (NA), 1550-nm MFD, cut-off wavelength, background loss and 1532-nm absorption of the fiber are 0.23, 5.9 $\mu$m, 950 – 1050 nm, 200 dB/km (1200 nm) and 20 dB/m, respectively. The gross insertion losses of the pumping light into and out of the fiber are 0.5 and 1.5 dB (1535 nm), respectively. The amplified spontaneous emission (ASE) spectrum (shown in Fig. 3, peak wavelength: 1534.96 nm, peak power: −4.4 dBm) of the pumped $Er^{3+}/Yb^{3+}$ co-doped fiber was monitored with an Anritsu MS9710B optical spectrum analyzer (operation wavelength range: 0.6 – 1.75 mm, resolution adopted: 0.1 nm). The reflection spectra of $FBG_1$ and $FBG_2$ were shown in Figs. 4 and 5. As shown in Figs. 6 and 7, the characteristics of output power and spectrum of the fiber laser were measured with an optical power meter (NOYES OPM4) and the spectrum analyzer, respectively, when the pump power was 69 mW. The linewidth of output laser was measured as 0.072 nm by 3 dB and 0.192 nm by 25 dB at 1552.08 nm (resolution adopted: 0.07 nm). Its power stability was $< 5\%$, side mode suppression ratio was 59 dB and the output wavelength stability was ±0.01 nm.

The pump threshold (12 mW) of the fiber laser can be got via the intersection between the extended line of $P_{\text{out}}$-$P_2$ curve and abscissa in Fig. 6. Its accuracy can be verified through comprehensive measurments of optical spectrum analyzer (OSA) and optical power meter (OPM). If we decrease or eliminate the large splicing joint loss, we can achieve a much lower threshold.

The slope efficiency is defined as

$$\eta = \frac{P_{\text{outmax}}}{P_2 - P_{\text{th}}} \times 100\%, \qquad (1)$$

where $P_{\text{outmax}}$ is maximum output power of the fiber laser, $P_{\text{th}}$ is pump threshold of the fiber laser, and $P_2$ is output power of the 99% port of the coupler.



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LMkr  C:                  D:               C-D:
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Peak.........    1551.84nm  -22.66dBm  FWHM(2.35σ)...    2.609nm
Mean Wl(25dB).   1553.52nm             Pk Dens(/1nm)..  -36.95dBm
Mean Wl(FWHM).  1551.939nm             Total Power...   -12.55dBm
25dB Width....      6.88nm
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Res:0.1nm          /    Avg:Off          /  Smplg:501  /
VBW:1kHz           / Sm:Off  / Intvl:Off   /              / Att On
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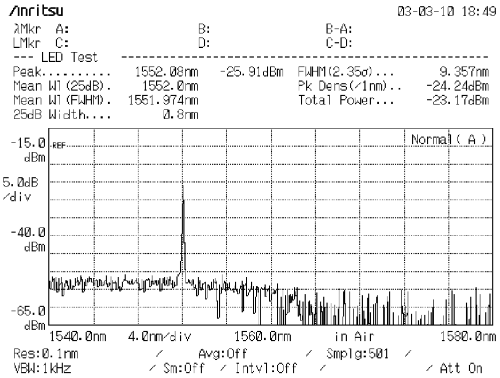
Fig. 4. Reflection spectrum of the $FBG_1$.



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λMkr  A:                  B:               B-A:
LMkr  C:                  D:               C-D:
--- LED Test   -------------------------------------------------
Peak.........    1552.08nm  -25.91dBm  FWHM(2.35σ)...    9.357nm
Mean Wl(25dB).    1552.0nm             Pk Dens(/1nm)..  -24.24dBm
Mean Wl(FWHM).  1551.974nm             Total Power...   -23.17dBm
25dB Width....       0.8nm
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Res:0.1nm          /    Avg:Off          /  Smplg:501  /
VBW:1kHz           / Sm:Off  / Intvl:Off   /              / Att On
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Fig. 5. Reflection spectrum of the $FBG_2$.

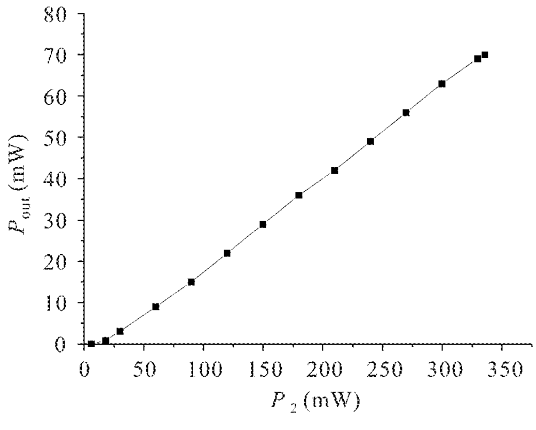
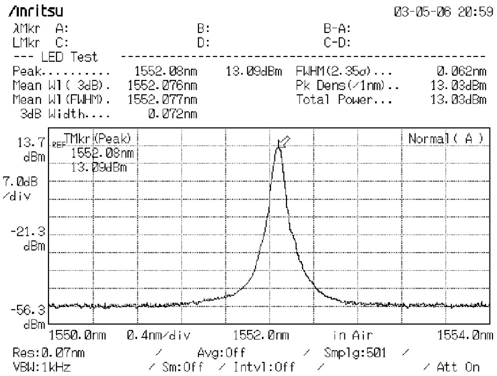


Fig. 6. Output power of the DBR $Er^{3+}/Yb^{3+}$ co-doped fiber laser as a function of absorbed pump power.



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/inritsu                                                 03-05-06 20:59
λMkr  A:                   B:                 B-A:
LMkr  C:                   D:                 C-D:
--- LED Test   ------------------------------------------------------
Peak..........  1552.08nm    13.09dBm  FWHM(2.35σ)...        0.062nm
Mean Wl( 3dB). 1552.076nm              Pk Dens(/1nm)..     13.03dBm
Mean Wl(FWHM). 1552.077nm              Total Power...      13.03dBm
 3dB Width....    0.072nm
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```
Res:0.07nm          /      Avg:Off        /  Smplg:501  /
VBW:1kHz          / Sm:Off  / Intvl:Off    /                 / Att On
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Fig. 7. Output spectrum of the $Er^{3+}/Yb^{3+}$ co-doped fiber laser.

Accordingly, the slope efficiency (22%) can be calculated as

$$\eta = \frac{69}{329.61 - 12} \times 100\% \approx 22\%.$$

The relationship of $P_1, P_2$ and $P_3$ is

$$-10\lg\frac{P_3}{P_1} = IL, \qquad (2)$$

where $P_1$ is laser power launched into the coupler, $P_3$ is output power of the 1% port of the coupler, and $IL$ is insertion loss from port 1 to port 3 at 1064 nm (its value is 17.82 dB).

So, from Eq. (2), we can educe

$$P_2 = P_1 \times 99\% = P_3 \times 10^{1.782} \times 99\%. \qquad (3)$$

Therefore, from the OPM connected to port 3, we can get the output light power from port 2 (the power launched into the resonance cavity) and monitor $P_2$ and the power stability of the 1064 nm pump.

The laser had a maximum output power of 69 mW (absorbed pump power $P_2 = 329.61$ mW), which can be seen from Fig. 6. We also tried to get even higher output power. Yet, the output laser gradually became saturated and the $P_{\text{out}}$-$P_2$ curve turned nonlinear accordingly. The wavelength of output laser strictly coincided with the fiber Bragg wavelength, as the resonant-cavity structure was simple and $FBG_2$ was a narrowband feedback component. Throughout the experiment, the linewidth was independent of the output laser power.

Till now, we have not found same experimental devices reported concerning DBR $Er^{3+}/Yb^{3+}$ co-doped fiber lasers with a 1064-nm Nd:YAG pump via extensive search.

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