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High power, low noise Yb-ring-doped cladding-pumped three-level fiber laser

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Abstract

We report high-power, cladding pumped, Yb-doped fibre lasers and an ASE-source operating at 977 nm. Sources are capable of delivering up to 2 W of fibre-coupled, single-moded output power with slope efficiency as high as 68%. High power and high slope-efficiency are achieved by using high numerical aperature (>0.7), jacketed air-clad fibre and high brightness pump sources. Both type of sources exhibit relative intensity noise below –130 dB/Hz and are thus suitable for pumping DFB fibre lasers and other applications requiring low noise and/or high power.

Introduction

High power, compact, reliable and efficient single-frequency lasers have been a subject of significant technical and experimental activity in recent years. Several high power, single frequency lasers in the wavelength region of 1030-1100 nm based on solid-state, semiconductor and double-clad fibre lasers have been demonstrated (References?). However, at wavelength range of 970-980 nm especially attractive for pumping EDFAs, Raman fibre lasers, and pulsed sources there have been no practical implementations. Semiconductor laser based solutions using MOPA and flared designs have been reported in literature of being capable of delivering up to 1 W of optical power at 980 nm. However, their commercial deployment has been hindered by the problems in fibre coupling and performance reliability.

Double-clad fibres seem to be very promising candidates to be used in high power applications because of their ability to convert the power from broad-area semiconductor diodes very efficiently into high brightness, single-mode output. Fibre lasers are also easily scalable in output powers, provide simple delivery of the laser beam, are very compact and do not suffer from heat dissipation problems as opposed to solid-state lasers. So far the problem in developing an efficient Yb-doped fibre laser at ~977 nm has been mainly caused by the difficulty to achieve sufficient enough inversion to produce the lasing action because of the quasi-three level transition around 1040 nm and large re-absorption around ~977 nm. Additionally, Yb-doped fibre lasers are known to be very noise and exhibit poor relative intensity noise (RIN) that will limit their potential application range especially the use as a pump source for ultrashort pulse generation in ultrafast spectroscopy, multiphoton microscopy and the pumping of parametric devices. To stabilize the fibre laser and to increase the efficiency of the laser several methods have been suggested such as fibre Bragg gratings, unidirectional ring cavity and ring-doping.

In this paper, we present two practical implementations of high-power cladding-pumped Yb-doped fibre pump source operating at 977 nm: Yb-doped fibre laser and an ASE-source. We also present detailed performance data on the sources made possible by recent advances in high power multimode pump diodes and fibre technology. Fibre sources are capable of delivering up to 2 W of output power with the relative intensity noise below −140 dB/Hz.

Configuration of the fibre sources

To make an efficient, high-power fibre laser suitable for wide range of applications it has to have three characteristics: low threshold, high slope efficiency and low RIN. Cladding-pumping with high-power multimode diode pump sources is the preferred way to produce multi-watt, single-mode fibre lasers. Double-clad fibres have a doped single-mode core surrounded by two cladding layers. The diameter of the inner cladding is typically several orders of magnitude larger than the core diameter in order to provide efficient coupling of the low brightness, broad-area laser diodes. In double clad fibres the overlap between the pump field and the doped core is small and hence the threshold pump powers for these devices are high. However, as the available pump power is almost unlimited this does not generally create any problems. The difficulty to achieve lasing threshold at 977 nm in Yb-doped lasers is caused by the gain created by the quasi-three level transition at ~1030 nm. As the overlap of the pump field with the gain medium is small, the fibre length required to absorb sufficient amount of pump power to create over 50% inversion at 977 nm is long and the unwanted gain at 1030 nm with weak re-absorption becomes so high that the spurious oscillations cannot be suppressed.

The threshold of the laser can be lowered by reducing the cladding-and-core ratio as the threshold of the laser is proportional to the cladding diameter. At the same time also the NA of the fibre is required to be high in order to have high coupling efficiency between pump diode and the fibre. To increase the NA of the Yb-doped fibre we use jacketed air-clad (JAC) geometry which is based on robust reproducible conventional silica fibre technology. With this technology NA higher than 0.7 can be achieved. Figure 1 shows a cross section of the Yb-doped JAC fibre, with white light launched into the inner cladding and emerging through the imaged end. The multimode inner cladding is supported by a thin glass mesh with a wall thickness comparable to the wavelength. This resulted in very low pump leakage and hence high numerical aperture. The core is single-moded with a cut-off of 950 nm. The pump absorption is 6 dB/m.

In order to suppress unwanted gain at 1040 nm we have utilized ring-doping of Yb ions [3]. Ring doping decreases the gain at all wavelengths reducing the overlap between the pump and lasing fields. As the inversion is increased by higher pump power the gain at 977 nm is enhanced in relation to unwanted gain as absorption and emission cross-sections are higher at 977 nm. Thus, the lasing threshold at 977 nm is reduced relative to the fixed length of the Yb-doped fibre.

Yb-ions have a relatively narrow emission bandwidth (~4 nm) centered at 977 nm. Hence the high power output can be achieved from a simple amplified spontaneous emission (ASE) source or from laser configuration using broadband feedback from a mirror or wavelength selective narrowband reflectors such as fibre Bragg gratings. The configuration of the sources is shown in Fig. 2. For the ASE source, the Yb-doped JAC-fibre was spliced to another fibre with an angled output facet that suppressed feedback. This makes the output nearly uni-directional even with a simple perpendicular cleave (4% reflecting) in the pump launch end of the fibre. For the laser configuration, a fibre Bragg grating with reflectivity ~10% was spliced to the output end of the JAC-fibre, while the laser was pumped through a broadband dichroic mirror that provided feedback in the other end of the cavity. Both sources used a 915 nm diode pump.

The output power and slope efficiency of the sources is shown in Fig. 3. Fibre laser has high output power (1.4 W) and slope efficiency (68%) than the ASE-source. Other additional benefit of the laser configuration is that the output is less sensitive to back-reflection. The drawbacks of the laser configuration compared to the ASE-source are higher threshold power (~450 mW), more complex structure and as will be shown later there are high RIN peaks at the relaxation oscillations frequency and at frequencies corresponding to the cavity round trip time. The output power of the ASE-source is 1.2 W and the slope efficiency is 37%. The benefits of ASE-source are lower threshold (~120 mW) and a simple structure as no external feedback is required to produce emission at 977 nm. Since the output is seeded by spontaneous emission, the RIN is essentially white, and the output essentially unpolarized even in the presence of weak polarizing effects. This is especially desirable in applications such as pumping EDFAs and DFB fibre lasers where the variation of the polarization state of the pump have been shown to affect the device performance. Drawbacks of the ASE-source are lower efficiency and inherent sensitivity to back-reflections (isolators for 980 nm do exist, but they are bulky, lossy, and expensive).

The output spectrum of the sources is shown in Fig. 4. As shown in the inset, the suppression of emission at ~1040 nm is more than 20 dB for both sources. The spectral width of the ASE source is 3 nm and the centre wavelength is situated at 977 nm, which is practically at the peak of the 980 nm absorption band of erbium-ions in silica glass. The spectral width of the fibre laser was 0.5 nm, mainly determined by the characteristics of the reflective grating.

In some applications, such as pumping of DFB fibre lasers (DFB FLs) [5], the temporal stability of Yb-doped fibre-based pump source is as important as the wall-plug efficiency and output power. Figure 5 shows the RIN spectrum of the 977 nm fibre laser and ASE sources. The ASE-source has no cavity and hence its RIN is white, without any peaks arising, e.g., from relaxation oscillations or other cavity effects. The RIN of the ASE-source is below –130 dB/Hz and thus does not generate any extra contribution to RIN of the DFB FL. Hence, the ASE-source is an ideal pump source for DFB FLs in CATV and WDM systems. However, as the shot noise limit of the pump absorption is –153 dB/Hz the RIN below 1 kHz increases with RIN of the pump for all values above the shot noise limits. This may be a concern for some sensing applications for DFB FLs where the low-frequency range is of specific interest. As can be seen from Fig. 5, the fibre laser pump source has several RIN peaks. The relaxation oscillation peak occurs at 450 kHz at a RIN level of –100 dB/Hz. The RIN peak at 30 MHz is dependent on the cavity length and hence on the position of the grating output coupler. In our measurements the cavity length was 3.3 m. The additional peaks in the RIN spectrum are harmonics of the beat frequency of the longitudinal modes within the laser cavity. Outside the peaks the RIN of the fibre laser is very low and limited only by the sensitivity of the measurement device (~ –145 dB/Hz). Thus by optimising the device length of the fibre laser, it should be a suitable pump source for DFB FLs in both analogue CATV and digital WDM systems.

Conclusions

We have presented results on high-power 977 nm Yb-doped fibre sources based on jacketed air-clad fibre technology and having two different configurations: ASE-source and fibre laser. The fibre laser was capable of delivering 2 W output power. We also demonstrated a fibre laser with a slope efficiency of 68%. To our knowledge both of the results are highest achieved from a single-mode fibre source at 980 nm. ASE-source had an output power of 1.2 W with slope efficiency of 37%. Both type of sources exhibit RIN below –130 dB/Hz and are thus suitable for pumping DFB fibre lasers and other applications requiring low noise and/or high power.

References

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Figure captions

Figure 1. Cross section of jacketed air-clad (JAC) fibre. Inner cladding diameter 20 ì m, NA 0.7.

Figure 2. Schematic configuration of the JAC ASE-source and fibre laser.

Figure 3. Output power and slope efficiency of the JAC fibre laser and ASE-source as a function of absorbed pump power. Threshold and slope efficiency for ASE source is 120 mW and 37% and for fibre laser 400 mW and 68%.

Figure 4. Output spectra for laser and ASE source configurations.

Figure 5. Relative intensity noise graphs of the fibre laser and ASE fibre source operating at~ 977 nm.

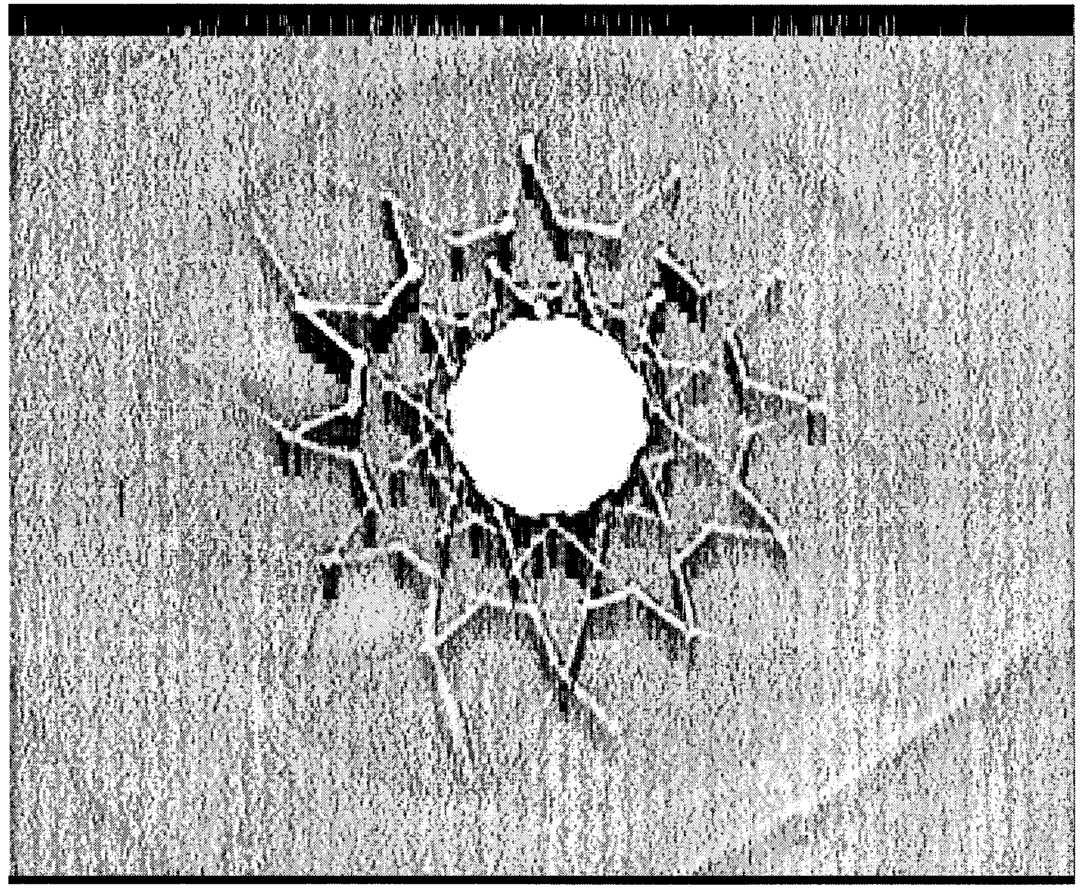


Figure 1.

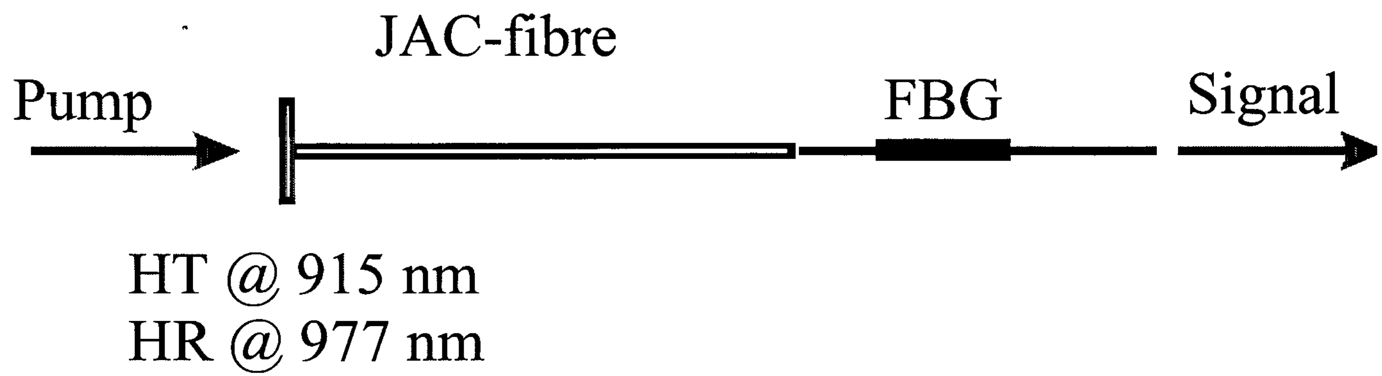
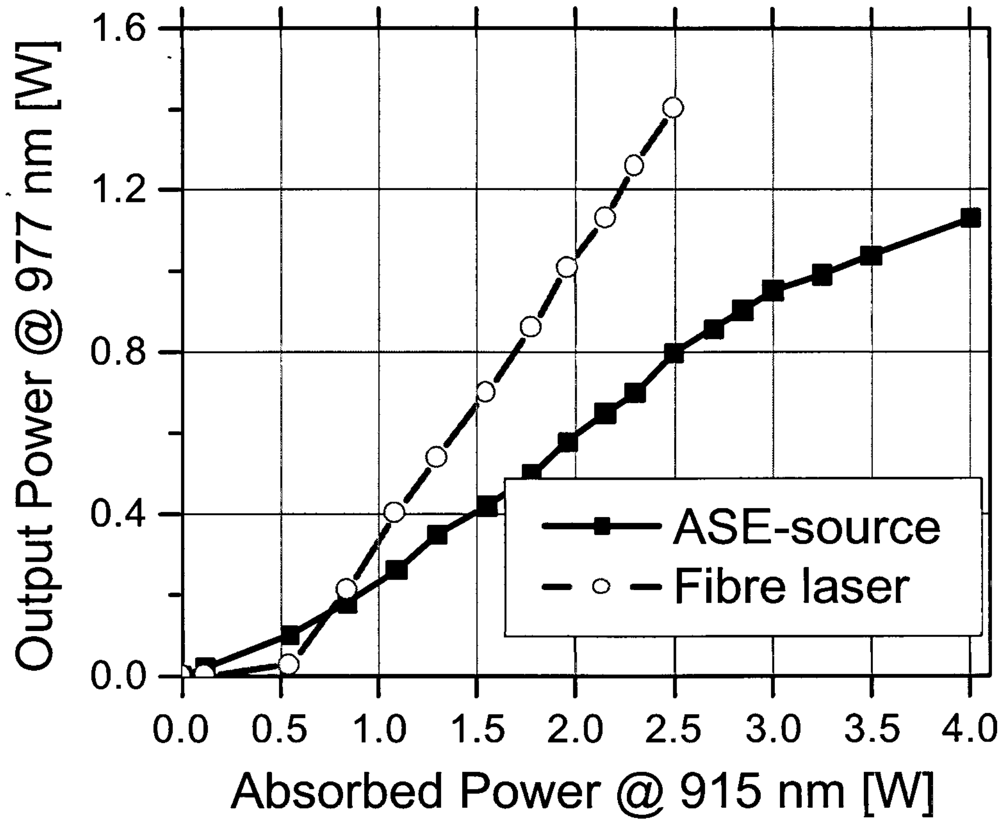


Figure 2



Output Power @ 977 nm [W]
1.6
1.2
0.8
0.4
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Absorbed Power @ 915 nm [W]
ASE-source
Fibre laser

Figure 3

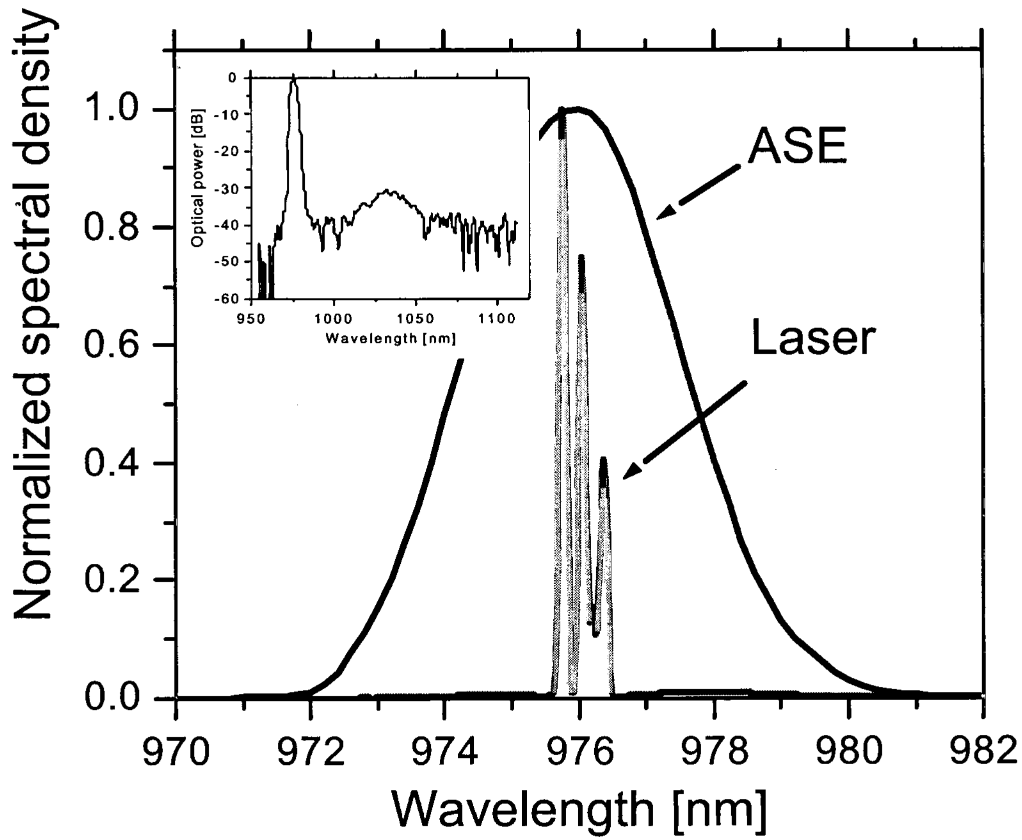
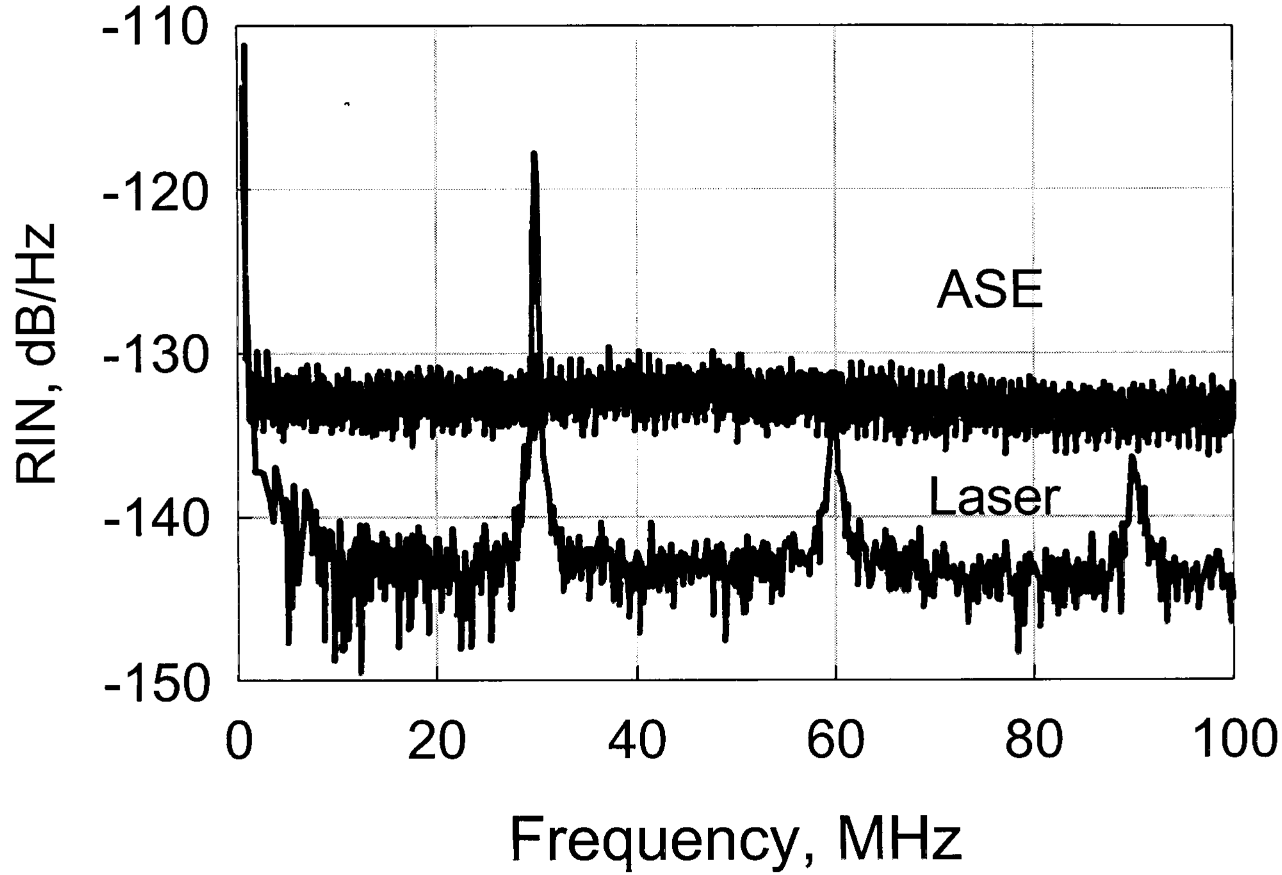

Normalized spectral density
1.0
0.8
0.6
0.4
0.2
0.0
970
972
974
976
978
980
982
Wavelength [nm]
ASE
Laser
Optical power [dB]
0
-10
-20
-30
-40
-50
-60
950
1000
1050
1100
Wavelength [nm]

Figure 4



-110
-120
-130
-140
-150
RIN, dB/Hz
ASE
Laser
0
20
40
60
80
100
Frequency, MHz

Figure 5