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# A highly efficient all-glass double-clad ytterbium doped holey fiber laser

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**Abstract:** We report an all-glass double-clad ytterbium doped holey fiber and a highly efficient diode-pumped fiber laser based upon this fiber. The output power of our CW laser exceeds 1W with greater than 80% efficiency.

**OCIS codes: (140.0140)** Lasers and laser optics; **(140.3510)** Lasers, fiber

Holey optical fibers (HFs) can offer novel optical properties that cannot be obtained by conventional fibers. They can be made of a single material, and can exhibit broadband single modeness[1], thereby allowing an alternative route for large modear ea fibers (LMAs)[2]. This is particularly attractive for high power active devices. Here, a novel all glass cladding-pumped $Yb^{3+}$-doped HF is reported, where different sizes of air holes are arranged to form a double-clad structure assh own in Fig.1 (also see ref.[3]). However, when both rare-earth and charge-compensating dopants are incorporated in a HF core, the refractive index of the core is naturally altered. This affects the core NA, and broadband single mode operation can be lost. We use aco nventionall ow-NA LMA fiber preform (NA~0.05, $Yb^{3+}$ concentration~3000ppm by weight) to overcome this issue (cf. approachu sed in [4]). Note that with this low value of NA, lighti s no longer guided in a conventionalf iber form in practicedue to extreme bendl oss. Therefore, the holes in the inner-cladding of the HF (see Fig.1) dominate the light guidance, while single mode operation is also retained. The fiber outer diameter is 175μm. The hole diameter $d$ andd istance between two adjacent air holes $\Lambda$ are 2.7μm and 9.9μm, respectively. The inner-claddingd iameter is ~140μm, while the thickness of the outer-cladding is ~2$\Lambda$. Thear ea of the doped region is $\pi\Lambda^2/4$=77μm$^2$. Since the effective modea rea was measured to be ~120μm$^2$ at 1047nm, the modal overlap with the doped region is more than6 0%. Note that an off-centered core is deliberately introduced in order to enhance the pump absorption.

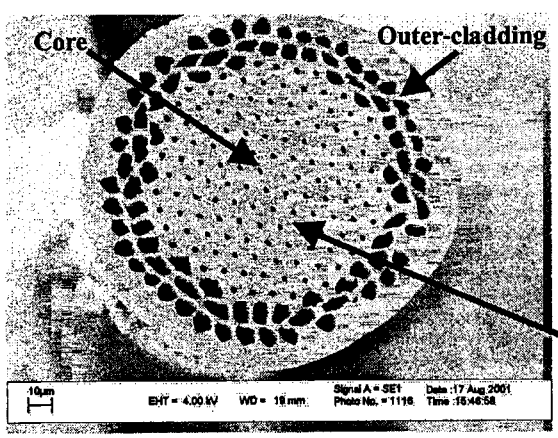


Fig.1 A SEM photograph of the all-glass double-cladyt terbium doped holey fiber.

We measured power conversion efficiencies for this fiber by pumping at 976nm (single-mode Ti:sapphire laser) and at 915nm (Laser diode: spot size 100μm and NA=0.22). The power conversion efficiencies are 82% using a 4m length and7 0% using a 7.5m length, respectively, and the output power exceeds 1W in thec ase of 915nm pumping owing to the increased pump power available from the laser diode.

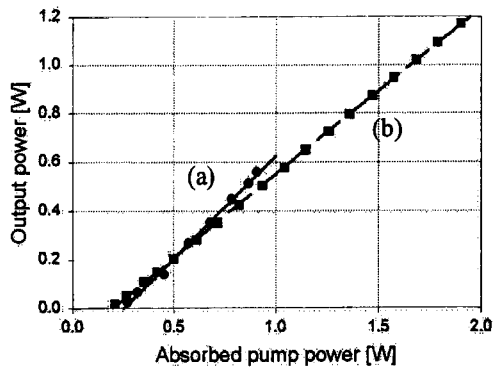


Fig.2 The output characteristics of CW laser output,p umping at 976nm(a) and at 915nm(b).

By inserting first an acousto-optic modulator, and then an acousto-optic tunable filter, we actively Q-switched and mode-locked this laser. Up to5 0μJ pulse energy was obtained at 1kHz repetition rate in the Q-switching experiment. We note that no thermal fracture was observed even when u sing h igh pu mp po wers. In the mode-locking experiment, a broad tunability was obtained as shown in Fig.3 under stable fundamental mode-locking op eration (pulse duration ~100psec). This implies that it is, in principle, possible to obtain ultrashort multi-nJ pulses at 1μm by employing an appropriate mode locking technique.

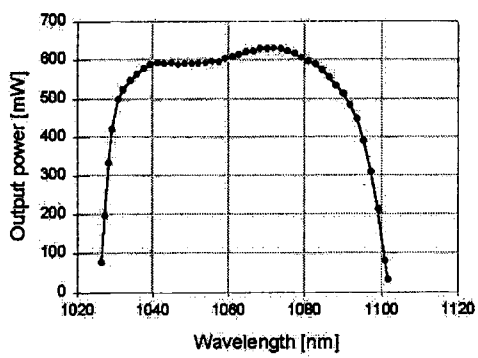


Fig.3T uning curve of ML laser ($P_{pump}$ ~1.33W). More than 500mW output was obtained over 60nm.

In summary, we present a highly efficient single-mode all-glass double-clad ytterbium doped HF laser and show that HF technology allows versatile designs for cladding pumped fibers. A technique for achieving single-mode operation in HFs while incorporating with active dopants is also d iscussed. Under CW operation, the power conversion efficiency is measured to be more than 80%, which is comparable to the best conventional ytterbium doped fiber lasers. Furthermore, Q-switching and mode-lockingop eration of this fiber laser is demonstrated.

## References

[1] T.A.Birks, J.C.Knight, and P.St.J.Russell, "Endlessly single-mode photonic crystal fiber," *Opt.Lett.*, 22, pp.961-963 (1997)

[2] J.C.Knight, T.A.Birks, R.F.Cregan, P.St.J.Russel and J.-P. de Sandro, "Large mode area photonic crystalf iber," *Electron.Lett.*34,pp.134 7-1348 (1998)

[3] C.C.Renaud, J.K.Sahu, K.Furusawa, R.J.Selvas-Aguilar, J.Nilsson, and D.J.Richardson, "A new fibre design toobta in wide tunable operation with a doubleclad Ybdo ped fibre laser," *Electron.Lett.* Vol.37, pp.1116-1117 (2001)

[4] W.J.Wadsworth, J.C.Knight, and P.St.J.Russell, "Large mode area photonic crystal fibre laser," in OSA Trends in Optics and Photonics Vol.56, ConferenceonL asers and Electro-Optics (CLEO 2001), Technical Digest, Postconference Edition (Optical Society of America, Washington DC, 2001),p.3 19