Diffraction limited polarized emission from a multimode Yb fiber amplifier after nonlinear beam converter

Laurent Lombard, Arnaud Brignon, Jean-Pierre Huignard, Eric Lallier, Gaëlle Lucas-Leclin, Patrick Georges, Gilles Pauliat, Gérald Roosen

Diffraction-limited polarized emission from a multimode ytterbium fiber amplifier after a nonlinear beam converter

L. Lombard, A. Brignon, J. P. Huignard, and E. Lallier

Thales Research and Technology—France, Domaine de Corbeville, 91404 Orsay, France

G. Lucas-Leclin, P. Georges, G. Pauliat, and G. Roosen

Laboratoire Charles Fabry de l'Institut d'Optique du Centre National de la Recherche Scientifique et de l'Université Paris Sud, Centre Universitaire, Bâtiment 503, 91403 Orsay, France

Received October 28, 2003

The multimode and depolarized output beam of a highly multimode diode-pumped Yb-doped fiber amplifier is converted to a diffraction-limited, linearly polarized beam by a self-referencing two-wave-mixing process in an infrared-sensitive photorefractive crystal (Rh:$BaTiO_3$). As much as 11.6 W of single-mode output is achieved with a 78% multimode-to-single-mode photorefractive conversion efficiency. © 2004 Optical Society of America

OCIS codes: 060.2320, 190.5330, 190.7070.

Much progress has been made with single-mode Er- or Yb-doped fiber lasers and amplifiers in the past few years since output power exceeding 400 W was demonstrated with a nearly diffraction-limited beam quality in a conventional single-mode fiber.[1,2] In pulsed operation, peak powers of a few kilowatts have been demonstrated.[3] However, a further increase in power is limited by nonlinear effects and material damage caused by the huge power density carried along the core of the fiber. An efficient way to limit the contribution of these mechanisms is to decrease the power density by increasing the core diameter D and lowering the numerical aperture (NA). Indeed, the product $D \times \mathrm{NA}$ has to be kept below a limit to maintain single-mode propagation; otherwise the propagation becomes multimode and the beam quality is degraded. Recently, significant efforts have been devoted to new techniques, such as maintaining a single transverse-mode propagation in multimode fiber amplifiers[4] or using large-mode-area, low-NA fiber lasers[5] or amplifiers.[6]

An alternative original approach, first proposed in Ref. 7, consists of correcting the beam profile after the multimode amplifier by use of a nonlinear beam cleanup method. The photorefractive two-wave-mixing beam cleanup interaction has been validated in previous work in visible light[8,9] after a depolarizer[10] and at 1064 nm after an aberrator.[7,11] In this Letter we propose and demonstrate an improved version of this technique applied to a diode-pumped multimode Yb-doped fiber amplifier.

Diffusion-type photorefractive materials allow energy transfer between two coherent beam by interference-induced index grating. In particular, a low-power single-mode beam can be mixed with a coherent high-power multimode beam, so that the interference-induced index grating diffracts the high-power beam along the single-mode beam with the phase characteristics of the single-mode beam. In other words, photorefractive two-wave mixing acts as a nonlinear spatial mode converter.[7] With the crystal used in this experiment both beam polarizations must be in the same plane as the crystal c axis to achieve maximum efficiency.

In this Letter the technique is applied to a diode-pumped multimode Yb-doped fiber amplifier as shown in Fig. 1. A cw master oscillator (Nd:YAG nonplanar ring oscillator laser, 500 mW at 1.06 μm, spatially and spectrally single mode) is amplified in a multimode fiber amplifier. The amplifier uses a double-clad fiber[12] with a 55-μm-diameter (NA, 0.19) Yb-doped signal core (6500 mol parts in 10^6 Yb_2O_3) and a 340–400-μm-diameter (NA, 0.38) D-shaped pump core. The 3.5-m-long fiber absorbs a power of 60 W

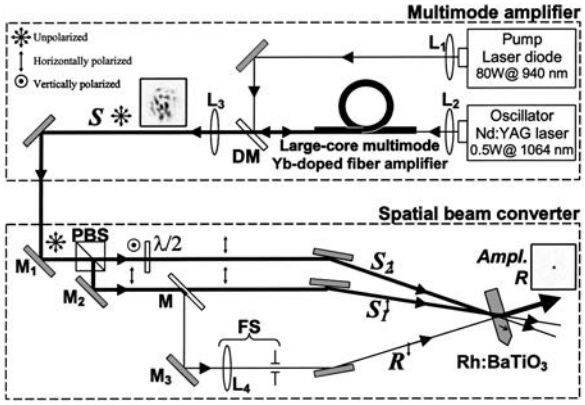

Fig. 1. Experimental setup of an Yb-doped multimode fiber amplifier with a spatial beam converter. The amplified depolarized multimode signal beam S is split into its two linear polarizations, combined with an extracted single-mode beam R in a Rh:$BaTiO_3$ crystal, and converted to single mode. DM, dichroic mirror to separate 940- and 1064-nm beams; L_1, L_2, L_3, lenses; M_1, M_2, M_3, mirrors; $\lambda/2$, half-wave plate; PBS, polarizing beam splitter; M, spot mirror of the size of one speckle grain of S; FS, spatial filtering device. Signal and amplified reference spot shapes are shown in squares. An arrow in the crystal indicated the c-axis orientation.

0146-9592/04/090989-03$15.00/0

of the 940-nm pumping diode. The amplified signal beam S has a power of 18 W, is depolarized, and bears many transverse modes, as seen in Fig. 1. All the speckle grains have a different elliptical polarization but are coherent with each other. A 55-μm core diameter fiber is used in this experiment, but the approach is scalable to significantly larger core diameters.

To treat its two polarizations, S is split into its two linear components S_1 (horizontal polarization) and S_2 (vertical polarization, changed to horizontal polarization by a half-wave plate; see Fig. 1). The powers of S_1 and S_2 are 8.3 and 6.6 W, respectively. A diffraction-limited reference beam R is created by spatially selecting a small part of one of the bright speckle grains of S_1 with a dot mirror. This mirror is a 1-mm-diameter gold spot coated on a high-transmission plate. The reflected grain, which is almost diffraction limited, is spatially filtered with a lens–pinhole system. This resulting 110-mW reference beam R is horizontally polarized, diffraction limited, and coherent with S.

S_1 and S_2 are then mixed with the reference beam R in the photorefractive crystal. This Rh:$BaTiO_3$ crystal[13] has a roof shape to prevent any parasitic oscillation arising from beam fanning.[14] The 8 mm $\times$ 8 mm input and output faces are antireflection coated and cut at 45° from the crystal c axis. This c axis lies in the horizontal plane, the plane of the incident polarizations, to access large photorefractive gains. The crystal thickness is 3 mm. The measured photorefractive gain is 24.6 cm^{-1}. In the crystal plane, R is a 1.5-mm-diameter diverging beam normal to the crystal surface, and S_1 and S_2 are 1 mm $\times$ 1.5 mm diameter converging beams with a 40° incidence angle. The angle between S_1 and S_2 is 1.5°. Here, S_1 and S_2 spots are smaller than R, and they overlap and amplify the upper and lower halves, respectively, of R. S_1 and S_2 could also be the same size as R and overlap the whole beam.

The two-wave-mixing process in the photorefractive crystal then occurs as follows: The intensity fringes between R and S_1 are converted into a $\pi/2$-shifted index grating by the crystal. This grating diffracts S_1 along R and adds coherently the diffracted S_1 to R. As a result, R is amplified by S_1. The same process occurs between R and S_2. The remarkable property of this two-wave-mixing interaction is that it amplifies the intensity profile of R in the crystal but leaves the phase profile of R unchanged: S transfers only its energy and not its phase to R.

In this setup the reference R is in phase with the signals S_1 and S_2, even when the temperature fluctuates in the fiber. In an early version[15] reference beam R was taken directly on the oscillator before the amplifier. The phase fluctuations between R and S, induced by thermal and mechanical fluctuations in the fiber, had to be compensated because of the relatively slow photorefractive response. In this Letter the self-referencing interferometer gets rid of this problem because R, S_1, and S_2 are always in phase and no active phase stabilization is required.

Under these conditions, after the spatial beam converter we obtain an amplified R output power of 11.6 W with a 110-mW reference power and a 14.9-W total signal power $S_1 + S_2$ before the crystal. The power of S is 18 W at the spatial beam converter input, before mirror M_1 in Fig. 1. Behind the crystal the total signal is depleted to 2.7 W. Figure 2 shows R power versus time as it is amplified by S_1 alone, by S_2 alone, and by $S_1 + S_2$. The rise time is ~2–3 s and the two-wave-mixing power efficiencies are 77%, 82%, and 78%, respectively. Taking into account the 81% power transmission between the signal S at the fiber output and $S_1 + S_2$ before the crystal leads to a total power efficiency of 63% for the whole spatial beam converter. It is worth noting that most of these losses could be reduced by optimizing the optical elements' transmission with appropriate coatings. The low relative intensity noise of the nonplanar ring oscillator laser is degraded by the amplifier because of thermal effects, amplified spontaneous emission noise, and mechanical vibrations. The two-wave-mixing process does not significantly degrade the relative intensity noise. After the amplifier the long-term intensity stability is ~3% rms for $S_1 + S_2$ over 1 h.

The M^2 parameter is measured for the different beams with the second-order moment method. The results are shown in Fig. 3. Reference R is diffraction limited, the 11.6-W output beam is almost diffraction limited with $M^2 = 1.2$, and S_1 is multimode with

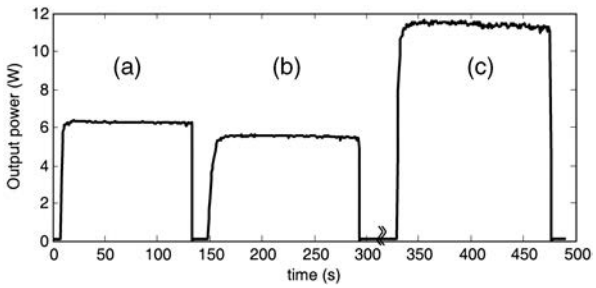

Fig. 2. Power evolution of R after the crystal (a) with S_1 on, (b) with S_2 on, and (c) with both S_1 and S_2 on. The rise time (from 10% to 90% of the full power) is ~2–3 s. The base level is the 110-mW R.

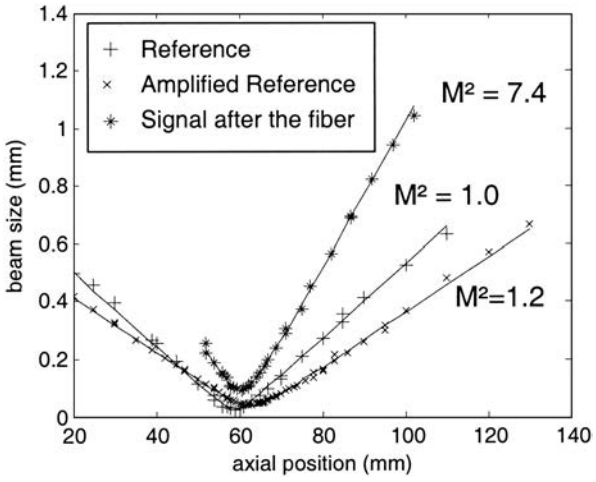

Fig. 3. Measure of the M^2 parameter for the different beams. Symbols represent the experimental points, and the solid curves are the corresponding fitted curves.

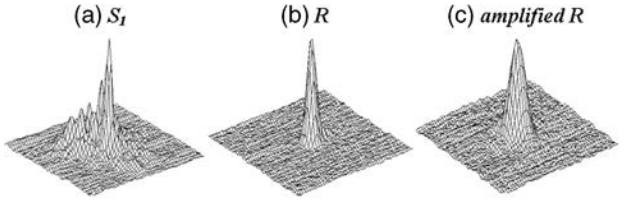

Fig. 4. Beam profiles: (a) signal S_1 at the fiber output, (b) extracted single-mode 110-mW reference beam R, (c) single-mode 11.6-W amplified R.

$M^2 = 7.4$. Amplified R is less diverging than R because of the additional converging thermal lens caused by residual absorption in the crystal. Figure 4 shows the intensity profiles of the waists in the far field.

After a constant illumination at 1.06 μm, we note a decrease of the two-wave-mixing efficiency in the Rh:$BaTiO_3$ crystal: In Fig. 2 a slight decrease is visible on the 11.6-W curve. As observed in Ref. 16, depoled horizontal lines appear in the crystal with a period of ~190 μm. This effect appeared after ~100 h of use. Applying a 200-mW green beam on the whole surface for several hours repoles the crystal and recovers the efficiency. This effect is similar to that reported in Ref. 16. Power handling of Rh:$BaTiO_3$ crystals was reported in Ref. 17 to be greater than 25 kW/mm^2 with cw illumination at 514.5 nm. Preliminary results with a Co:$BaTiO_3$ crystal are promising for high power handling at 1.06 μm because of the low absorption of this crystal at that wavelength.

Note that this beam-correcting system can be seen as a black box that converts any coherent depolarized multimode beam to a diffraction-limited, linearly polarized beam with the spectral characteristics of the beam emitted by the oscillator. The input beam can be highly multimode or aberrated, since the angular acceptance of the crystal is several degrees and its surface is ~1 cm^2 (equivalent to an $M^2 > 1000$). The required coherence length for the multimode signal is several millimeters or more, corresponding to the interaction length in the photorefractive crystal. Furthermore, the concept is applicable to pulsed operation since the very large core fiber could sustain high peak power.

In conclusion, we have experimentally demonstrated that the beam issued from a multimode Yb-doped fiber amplifier can be efficiently converted into a linearly polarized and nearly diffraction-limited beam. This original master oscillator power amplifier architecture involves a nonlinear photorefractive mode converter that allows beam cleanup by a self-referencing two-wave-mixing interaction. The emitted beam has the spatial and spectral qualities of the oscillator. The achieved output power with the components used in this experiment was 11.6 W with 78% photorefractive efficiency. The important feature is that the concept can be extended to very large core (several hundred micrometers) fiber amplifiers that will support very high powers (kilowatt cw levels) in the cw or pulsed regimes. Rh:$BaTiO_3$ has been used for proof of concept, but alternative crystals or nonlinear mechanisms can also be appropriate for reliable operation at the high power levels required in industrial applications.

L. Lombard's e-mail address is laurent.lombard@thalesgroup.com.

References

1. V. Dominic, S. MacCormack, R. Waarts, S. Sanders, S. Bicknese, R. Dohle, E. Wolak, P. S. Yeh, and E. Zucker, Electron. Lett. **35,** 1158 (1999).
2. V. P. Gapontsev, N. S. Platonov, O. Shkurihin, and I. Zaitsev, in *Conference on Lasers and Electro-Optics (CLEO)*, Vol. 89 of OSA Trends in Optics and Photonics Series (Optical Society of America, Washington, D.C., 2003), postdeadlined paper CThPDB9.
3. D. J. Richardson, P. Britton, and D. Taverner, Electron. Lett. **33,** 1955 (1997).
4. F. Di-Teodoro, J. P. Koplow, S. W. Moore, and D. A. V. Kliner, Opt. Lett. **27,** 518 (2002).
5. J. Limpert, A. Liem, H. Zellmer, and A. Tünnermann, Electron. Lett. **39,** 645 (2003).
6. A. Liem, J. Limpert, H. Zellmer, and A. Tünnermann, Opt. Lett. **28,** 1537 (2003).
7. A. Brignon, J. P. Huignard, and E. Lallier, Appl. Phys. B **72,** 789 (2001).
8. A. E. T. Chiou and P. Yeh, Opt. Lett. **10,** 621 (1985).
9. L. Mager, G. Pauliat, D. Rytz, M. H. Garrett, and G. Roosen, Nonlinear Opt. **11,** 135 (1995).
10. J. E. Heebner, R. S. Bennink, R. W. Boyd, and R. A. Fisher, Opt. Lett. **25,** 257 (2000).
11. A. Brignon, J. P. Huignard, M. H. Garrett, and I. Mnushkina, Appl. Opt. **36,** 7788 (1997).
12. From the Institute for Physical High Technology, Jena, Germany.
13. From D. Rytz, Forschungsinstitut für Mineralische und Metallische Werkstoffe—Edelsteine/Edelmetalle GmbH, Germany. Rh doping concentration is 1000 parts in 10^6 in the melt.
14. N. Huot, J. M. Jonathan, D. Rytz, and G. Roosen, Opt. Commun. **140,** 296 (1997).
15. L. Lombard, A. Brignon, J. P. Huignard, E. Lallier, G. Lucas-Leclin, P. Georges, G. Pauliat, and G. Roosen, in *Photorefractive Effects, Materials, and Devices*, P. Delaye, C. Denz, L. Mager, and G. Montemezzani, eds., Vol. 87 of OSA Trends in Optics and Photonics Series (Optical Society of America, Washington, D.C., 2003), pp. 547–550.
16. R. S. Cudney and M. Kaczmarek, Opt. Express **7,** 323 (2000), http://www.opticsexpress.org.
17. P. Mathey, S. Latour, P. Lompré, P. Jullien, D. Rytz, and B. Salce, Appl. Phys. B **71,** 523 (2000).