Holographic injection locking of a broad area laser diode via a photorefractive thin-film device

P. D. van Voorst[1], M.R. de Wit[1], H. L. Offerhaus[1], S. Tay[2], J. Thomas[2], N. Peyghambarian[2] and K. -J. Boller[1]

[1]*Department of Physics, Twente University, Enschede, The Netherlands*
[2]*College of Optical Sciences, University of Arizona, Tucson, Arizona*

p.d.vanvoorst@utwente.nl

Abstract: We demonstrate locking of a high power broad area laser diode to a single frequency using holographic feedback from a photorefractive polymer thin-film device for the first time. A four-wave mixing setup is used to generate feedback for the broad area diode at the wavelength of the single frequency source (Ti:Sapphire laser) while the spatial distribution adapts to the preferred profile of the broad area diode. The result is an injection-locked broad area diode emitting with a linewidth comparable to the Ti:Sapphire laser.

OCIS codes: (190.5040) Phase Conjugation; (140.3520) Lasers, injection-locked; (190.5330) Photorefractive optics; (090.2900) Optical storage materials; (160.5320) Photorefractive materials.

References and links

1. G.L. Abbas, S. Yang, V.W.S. Chan and J.G. Fujimoto, "Injection behavior of high-power broad-area diode lasers," Opt. Lett. **12,** 605 (1987)
2. S. Weiss, S. Sternklar and B. Fischer,"Double phase-conjugate mirror: analysis, demonstration and applications," Opt. Lett. **12,**, 114(1987)
3. T. Shimura, M. Tamura and K. Kuroda, "Injection locking and mode switching of a diode laser with a double phase-conjugate mirror," Opt. Lett. **18,** 1645 (1993)
4. S. MacCormack and J. Feinberg, "Injection locking a laser-diode array with a phase-conjugate beam," Opt. Lett. **19,** 120(1994)
5. K. Iida, X. Tan, T. Shimura, K. Kuroda, "Stable injection locking of diode lasers through a phase-modulateddouble phase-conjugated mirror," Appl. Opt. **36,** 2491 (1997)
6. K. Iida, H. Horiuchi, O. Matoba, T. Omatsu, T. Shimura and K. Kuroda, "Injection locking of a broad-area diode laser through a double phase-conjugate mirror," Opt. Commun. **146,** 6 (1998)
7. H. Horiuchi, T. Shimura,T. Omatsu, O. Matoba and K. Kuroda, "Narrow bandwidth operation of high-power broad-area diode laser using cascaded phase-conjugate injection locking," Appl. Phys. B., **68,** 1021 (1999)
8. F. Wang, A. Hermerschmidt, P. Pogany, S.X. Dou and H.J. Eichler, "Enhanced performance of a mutually pumped phase-conjugation setup using two photorefractive crystals," Appl. Phys. B. **72,** 755 (2001)
9. F. Wang, A. Hermerschmidt and H.J. Eichler, "High-power narrowed-bandwidth output of a broad-area multiple-stripe diode laser with photorefractive phase-conjugated injection," Opt. Commun. **209,** 391 (2002)
10. P.D. van Voorst, H.L. Offerhaus, K.-J. Boller, "Single-frequency operation of a broad-area laser diode by injection locking of a complex spatial mode via a double phase conjugate mirror," Opt. Lett. **31,** 1061 (2006)
11. S-C De La Cruz, S. MacCormack, J. Feinberg, Q.B. He, H.-K Liu, P. Yeh, "Effect of beam coherence on mutually pumped phase conjugators," J. Opt. Soc.Am. B, **12,** 1363 (1995)
12. O. Ostroverkhova, W. E. Moerner, "Organic photorefractives: mechanisms, materials and applications," Chem. Rev. **104,** 3267 (2004)
13. G. Li, M. Eralp, J. Thomas, S. Tay, A. Schülzgen, R.A. Norwood, N. Peyghambarian, "All-optical dynamic correction of distorted communication signals using a photorefractive polymeric hologram," Appl. Phys. Lett. **86,** 161103 (2005)

#84519 - $15.00 USD Received 26 Jun 2007; revised 23 Aug 2007; accepted 22 Sep 2007; published 11 Dec 2007

14. S. Tay, J. Thomas, M. Eralp, G. Li, R.A. Norwood, A. Schülzgen, M. Yamamoto, S. Barlow, G.A. Walker, S.R. Marder and N. Peyghambarian, "High-performance photorefractive polymer operating at 1550 nm with near-video-rate response time," Appl. Phys. Lett. **87,** 171105(2005)
15. M. Eralp, J. Thomas, G. Li, S. Tay, A. Schülzgen, R. A. Norwood, N. Peyghambarian and M. Yamamoto, "Photorefractive polymer device with video-rate response time operating at low voltages," Opt. Lett. **31,** 1408(2006)

1. Introduction

Broad area lasers (BALs) can produce output powers up to several Watts. This high output power is achieved, however, at the cost of a poor spatial and spectral quality of the emitted radiation caused by the large gain area and wide output facet. Injection locking with a spectrally narrow laser of well-defined beamshape is known to readily narrow the spectrum of the locked BAL. Due to the inevitable spatial mode mismatch between the injected laser and the BAL direct injection locking is tied to small alignment tolerances [1], and stable reproducible injection locking is not always achieved. Since a double phase conjugate mirror (DPCM) setup was demonstrated by Weiss et al. [2] holographic locking using a DPCM has become a typical approach [3–10]. For holographic locking, a reference beam with high spectral quality and the beam of a BAL are combined in the crystal. Then, in a self-organizing way, the BAL can select a spatial mode while it is locked on the single frequency of the reference, resulting in an improved spectral quality of the beam. The hologram in such a setup like this converts the spatial mode of the single mode laser into a spatial distribution preferred by the BAL to lock the BAL in a stable way. It is also self-aligning, reducing the alignment demands. So far corresponding experiments have exclusively been based on inorganic photorefractive crystals, such as $BaTiO_3$.

However inorganic photorefractive crystals show severe disadvantages. For example, $BaTiO_3$ is a delicate material and depolarization can occur due to mechanical stress, and operation or storage outside a limited temperature range. It also has a high refractive index of about 2.4 giving rise to parasitic effects due to crystal-internal reflections. Another important drawback of such materials is their slow response, typically several minutes, such that phase-conjugate feedback cannot follow faster changes of the diode's output parameters as induced by, for example, changes of the drive current which modifies the output power. Finally, photorefractive crystals often require a large volume and longer interaction lengths (mm to cm) of overlapping beams inside the crystal in order to achieve locking. This also means that those parts of the beams that do not overlap have to travel significant distances through the the crystal as well, which can lead to the build-up of parasitic gratings [11] requiring additional suppression [5]. These disadvantages motivated us to investigate alternative photorefractive materials for their use in holographic injection locking.

An alternative class of photorefractive materials are polymers which have so far been investigated in the context of real-time holography and optical processing [12–15] due to their much shorter (ms) response times, their lower refractive index around 1.5 and their strong response requiring only sub-mm interaction lengths. With these properties compared to standard inorganic photorefractive crystals, there is considerable freedom in the choice of functional components. Additionally, the spectral and temporal response of a polymer system can be tailored using various additives and varying concentrations.

Here we demonstrate, for the first time, injection locking of a BAL through holographic feedback using a photorefractive polymer. As the signatures of locking we find that the BAL emits at a single-frequency concomitant with a temporal stabilization of the BAL output into its self-preferred, spatial mode pattern.

#84519 - $15.00 USD Received 26 Jun 2007; revised 23 Aug 2007; accepted 22 Sep 2007; published 11 Dec 2007

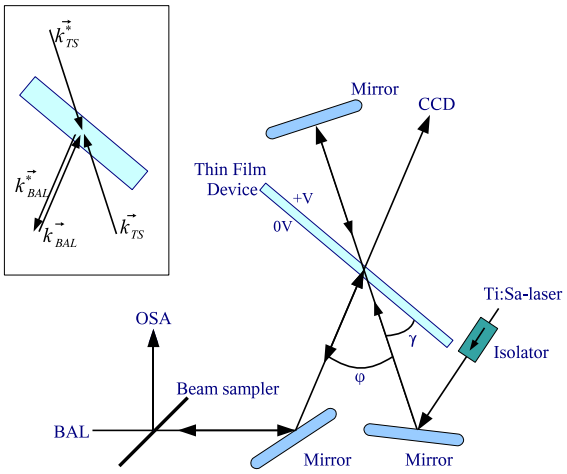

Fig. 1. Experimental setup. Insertion: Schematic of the k-vectors involved in the four-wave mixing ($\vec{k_{TS1}}$, $\vec{k^*_{TS1}}$)=Incoming and phase-conjugated k-vectors from the Ti:Sa laser, ($\vec{k_{BAL}}$)=k-vector from the BAL, ($\vec{k^*_{BAL}}$)=The generated phaseconjugate k-vector form the BAL.

2. Experiment

Figure 1 shows the configuration for chosen for locking with the wave vectors in the inset. The light from a continuous wave, single frequency (linewidth $<$10 MHz rms), TEM_{00} Titanium:Sapphire-laser (Ti:Sa, Coherent 899-01) is used as pump- and probe beam in a four wave mixing (FWM) configuration. The beam from the Ti:Sa laser and its retroreflected part intersect in a 105 μm thick photorefractive thin-film device as a standing wave pattern. The photorefractive polymer composite selected is PATPD:7-DCST:APDC:TNFDM:ECZ (39.8:25:25:0.2:10 wt%). In this composite, PATPD is the hole transporting polymer backbone, 7-DCST and APDC are electro-optic chromophores, TNFDM is the sensitizer dye which absorbs light and injects holes to the photoconducting polymer, and ECZ is the plasticizer used to reduce the glass-transition temperature of the composite. The photorefractive sample prepared is phase stable for several months under normal conditions. When tested under accelerated aging at 60 ^{o}C, the sample showed signs of phase separation after 5 hours. However, even after complete phase separation, the sample can be completely recovered by heating to 160 ^{o}C. The polymer is sandwiched between two ITO coated glass electrodes that are used to apply a DC bias of 4 kV to pole the electro-optic chromophores. The overall transmission of the photorefractive thin-film device is 70% $\pm$2%. Absorption is due to absorption of the polymer composite and Fresnel reflection losses at the glass-ITO electrodes. The light of the BAL enters the sample at Brewster angle, making losses due to reflections negligible. The entrance angle of the Ti:Sa is $70^{o} \pm 2^{o}$, resulting in a reflection of 4%. The absorption depends somewhat (2%) on the applied field and the presence of a grating because free charges absorb light. A passively cooled BAL (Sony SLD323V) emits the signal beam and is overlapped with the light from the Ti:Sa in the thin film (TF). The angles between the two beams, φ, and between the Ti:Sa beam and the TF, γ, are $20^{o} \pm 2^{o}$ and $13^{o} \pm 2^{o}$, respectively, as indicated in figure 1. The optical power on the TF from the Ti:Sa is 50 mW and the optical power from the BAL varied between 100 and 110 mW to tune the frequency of the passively cooled BAL. The beamspot of the Ti:Sa-laser beams projected on the TF is elliptical due to the non-zero angle of incidence. At the entrance of the TF, the BAL beam just fits within this ellipse with a long axis of about 5mm and a short axis of

#84519 - $15.00 USD Received 26 Jun 2007; revised 23 Aug 2007; accepted 22 Sep 2007; published 11 Dec 2007

about 3mm. The polarization of the lasers and the axis of fast divergence of the diode laser (its single spatial mode axis) lie in the plane of figure 1 The spectrum of the BAL is monitored by an optical spectrum analyzer (OSA, Ando AQ6317) with a resolution of 0.01 nm. The far field of the BAL is captured on a CCD camera (CCD).

The goal of this setup is that four-wave mixing in the TF diffracts light from the Ti:Sa beams into the phase-conjugated wavevector distribution of the BAL ($\vec{k^*_{BAL}}$) which travels back to the BAL for injection-locking. The advantage of such feedback is that it is only spectrally selective (because the phase-conjugating grating is induced by a single-frequency laser) while there is no spatial selectivity. Therefore no matter what spatially complex mode pattern the BAL emits or develops upon injection, locking should render single-frequency emission of the BAL in its preferred spatial mode pattern in a self-organizing way.

3. Results

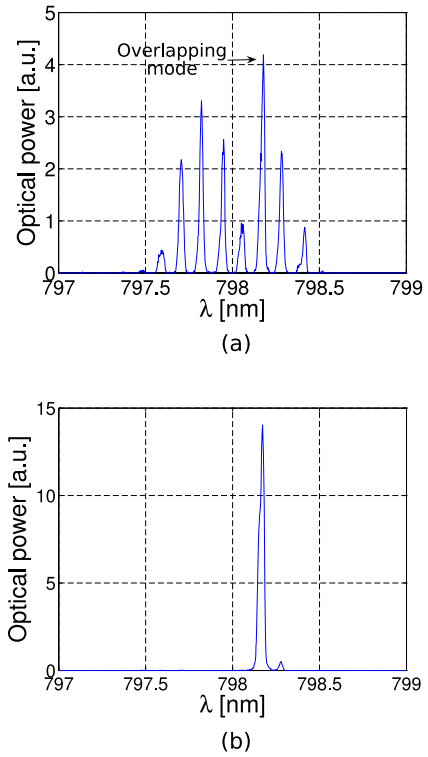

Fig. 2. Free running (a) BAL spectrum compared to locked (b).

In figure 2 the spectrum of the free-running BAL (top) is compared to the spectrum when the beam from the Ti:Sa laser beam is unblocked and the voltage at the TF is turned on (bottom). As can be seen, the broad, spectrally multi-mode, irregular spectrum of the BAL disappears and turns into a spectrum in which more than 98% of the power is emitted at the single wavelength of the Ti:Sa laser. The spectrum in figure 2(b) indicates that we successfully obtained injection locking by phase-conjugate feedback from the thin film polymer. Only a very small amount of light is still in some residual modes present. We note that locking was possible with any of the free running spectral modes of the BAL, as long as the BAL mode is spectrally matched to the Ti:Sa frequency. Achieving locking between modes is not possible. We adjusted the current

#84519 - $15.00 USD Received 26 Jun 2007; revised 23 Aug 2007; accepted 22 Sep 2007; published 11 Dec 2007

in the BAL to achieve the fine-tuning. The precision of the overlapping needed is below the resolution of the OSA. With the BAL locked the output observed on the CCD consists of a single mode along the fast (single mode) axis and a stable multimode pattern with multiple maxima along the slow (multi mode) axis. For the free running BAL the output pattern is blurred, washing out the intensity modulations along the slow axis. We ascribe the blurring to rapid fluctuations of the output mode and possibly different spatial output profiles for different frequency components. From this, we can conclude the spectral width of the locked signal is far below the 0.01nm resolution of the spectrum analyzer

So far, locking is achieved for up to 5 minutes. However, we observed that locking is maintained longer when the residual spectral drift of the BAL modes, caused by a temperature drift in the passively cooled setup, is minimized with tiny manual re-adjustments of the drive current. From this we expect that a standard temperature stabilization via a Peltier cooler would yield significantly longer locking times.

4. Summary and Conclusions

In summary, we have shown what we believe to be the first proof of principle of holographic injection locking of a broad area diode laser to the single frequency of a Ti:Sa using a photorefractive polymer. Using a passively cooled BAL locking is achievable up to 5 minutes. Extending the locking time by improving temperature stability allows for further experiments to investigate the locking at various powers for the master laser and the BAL. Since holographic locking in different configurations can also be used to improve the spatial beam quality besides the spectral quality, we believe it is useful to investigate alternative locking configurations.

Acknowledgments

The work at the Twente group is supported by the Dutch “Stichting Toegepast Wetenschappelijk Onderzoek” (STW). The Arizona group likes to acknowledge the final support from the US Air Force Office of Scientific Research.

#84519 - $15.00 USD Received 26 Jun 2007; revised 23 Aug 2007; accepted 22 Sep 2007; published 11 Dec 2007