# Long-term stable mode locking of a visible diode laser with phase-conjugate feedback

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We present a new method to obtain long-term stable phase-conjugate feedback (pcf) with a photorefractive crystal for a mode-locked semiconductor laser. The phase-conjugate mirror is a barium titanate crystal in a self-pumped internal reflection configuration, and the laser is a visible, antireflection-coated AlGaInP diode. We describe a new dynamic writing procedure for growth of an index grating in the photorefractive crystal that leads to stable pcf and discuss the reasons for this stability, which is the major advantage of this method over previously reported ones. Using this superior method, we achieve stable mode-locked operation of the laser with pulse widths of ~30 ps and a timing jitter of less than 2 ps.

Semiconductor lasers with phase-conjugate feedback have been investigated theoretically and experimentally from many different aspects; investigations have successfully taken place over the past decade on spectral narrowing, beam shaping of arrays, injection locking, noise properties, intensity dynamics, and mode locking.[1–8]

In the mode-locking experiments a major difficulty concerns the long-term stability of the phase-conjugate feedback when it is realized with photorefractive crystals, for example, barium titanate ($BaTiO_3$), in a self-pumped internal reflection geometry.[9] Until now in those experiments the refractive-index grating within the crystal was written under cw conditions and decreased rapidly when the rf modulation was turned on.[8] Segev *et al.*[7] demonstrated a stable setup that includes a grating to mode lock a diode array.

In this Letter we demonstrate first a new writing procedure that leads to long-term stable phase-conjugate feedback with a photorefractive crystal under mode-locking conditions of a semiconductor laser without the use of a grating. Second, investigating the optical spectra for different feedback procedures, we discuss why our dynamical writing procedure (DWP) is superior to earlier results.[7,8] We explain why the previously used method of Cronin-Golomb *et al.*[8] leads to a decrease of the phase-conjugate feedback.

Figure 1 shows a schematic depiction of our experimental setup. A Hitachi HL6714G 10-mW AlGaInP diode laser was removed from its TO can and mounted upon an open, passive heat sink. One side of the diode laser had a high-reflection coating ($R \approx 0.9$) provided by the manufacturer. We sputtered silicon nitride onto the opposite facet to create an antireflection coating that had a residual reflectivity of less than $10^{-3}$.

The high-quality antireflection coating of the laser diode causes an experimental difficulty: the diode does not show lasing even at high injection currents, and because of that lack of coherent light one cannot grow the refractive-index grating that is necessary for phase-conjugate feedback within the barium titanate crystal. To overcome this problem we construct an auxiliary cavity: the light that is reflected from the front facet of the crystal is reflected by a conventional mirror back into the laser. This gives sufficient feedback to start lasing.

The light emitted from the low-reflectivity facet is focused by a microscope objective onto the 6 mm × 6 mm × 6 mm cube of barium titanate. The angle of incidence onto the crystal is 81°. The distance from the laser to the front facet of the crystal is 50 cm, which refers to 300 MHz cavity round-trip frequency. The distance between the point of reflection on the

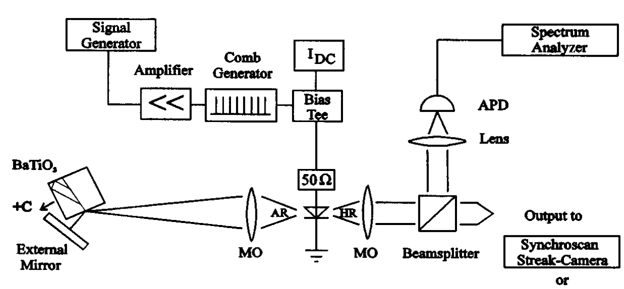


Fig. 1. Experimental setup. In the center is a laser diode with a high-reflectivity (HR) and a low-reflectivity (AR) facet. On top of the laser is the setup for the injection current that drives the laser. At the left of the laser is the barium titanate crystal (phase-conjugate mirror) and the auxiliary construction with the conventional mirror. To the right of the laser the detection branch is depicted. MO's, microscope objectives.

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barium titanate crystal and the high-reflectivity mirror was typically 2–3 cm.

The laser is actively mode locked by modulation of the injection current with short electrical pulses of a comb generator at 300 MHz. We tuned the dc current level and the frequency of the rf modulation to achieve the shortest satellite-free, mode-locked pulses.

The output light beam emitted from the high-reflection facet of the laser is collimated with a microscope objective and used to analyze the mode-locking performance. Diagnostic instrumentation includes a streak camera with 6-ps resolution, an optical spectrum analyzer with 0.1-nm resolution, and a high-speed avalanche photodiode whose output is displayed on a rf spectrum analyzer.

Our initial approach was to write the refractive-index grating in the barium titanate crystal with the laser driven by the dc current only. Buildup times when applying this method were 10–15 min. Once the phase-conjugate reflectivity was stationary, we blocked the conventional mirror and turned on the rf excitation. Typically we were just able to record mode-locked operation before the grating was erased; the phase-conjugate reflectivity degraded in this case within 2–5 min. This is similar to the observations of Cronin-Golomb *et al.*[8]

To improve the stability we tried next to grow the index grating with the diode-laser mode locked to the external conventional mirror cavity. A typical rf mode-locking frequency is 293.43 MHz. We were not able to grow any grating under those optimized mode-locked conditions. That is, when the laser was truly mode locked to the conventional mirror, no phase-conjugate mirror was formed even after 1–2 h.

Therefore we developed a new dynamical writing procedure (DWP) to grow the grating in the photorefractive crystal, leading to long-term stable phase-conjugate feedback under mode-locking conditions, as described below. First we establish lasing by use of the auxiliary mirror as described above. Then we turn on the rf modulation of the injection current with a frequency significantly below that needed for mode locking the laser in the cavity formed by the conventional mirror. A typical frequency for this operation is 292 MHz. At this point the optical spectrum analyzer shows a relatively narrow spectrum, and the streak camera displays a gentle temporal modulation with a long (0.5-ns) period. We fine tune the modulation frequency to obtain the narrowest optical spectrum. In this case typically two or three diode modes are present, which originate from the nonzero residual reflectivity of the antireflection-coated laser facet. In this case the phase-conjugate reflectivity quickly (1–2 min) grows, and finally the feedback from the phase-conjugate mirror dominates the feedback from the conventional mirror cavity (7:1). Gratings grown with this method are long-term stable under mode-locked operation, persisting for more than an hour with no adjustment.

Once the phase-conjugate mirror is operating we block the conventional mirror and adjust the modulation frequency and the dc current level for the best mode locking, i.e., the shortest satellite-free pulses. Figure 2 shows a typical streak-camera trace of a 29-ps (FWHM) pulse emitted from the laser with the stable phase-conjugate mirror. For this case the dc current-level was 43 mA, the rf power delivered to the comb generator was 0.9 W, and the rf frequency was 298.52 MHz.

To understand the observed behavior for the different growing procedures we will discuss in what follows the relation between the optical spectrum of the laser and the stability of the phase-conjugate feedback. Figure 3 shows optical spectra of the laser: Fig. 3(a) under dc injection current with phase-conjugate feedback grown under dc conditions, Fig. 3(b) mode locked to the conventional mirror cavity, and Fig. 3(c) mode locked to a stable (grown under rf excitation) phase-conjugate mirror.

In the case shown in Fig. 3(a) (dc conditions) the output of the laser is spectrally narrow (resolution limited), and hence the grating in the crystal grown under those conditions will reflect only a narrow part of any broader input spectrum. When we turn on the rf modulation in this case, the optical spectrum shows the appearance of the two adjacent diode modes. Those side modes do not fit the period of the written grating and consequently will start to erase it. The time scale of a few minutes for the decay of the phase-conjugate reflectivity under modulation is typical for such an erasure process.

If the laser is mode locked to the external conventional mirror cavity the optical spectrum is typically very broad, with structures that are due to the longitudinal mode structure of the solitary laser diode [Fig. 3(b)]. This spectrum is too broad to write an effective grating. We know from other experiments with bandwidth-limited pulses of 7 ps that it is this spectrum and not the pulse length of the mode-locked semiconductor laser that is responsible for the impossibility of growing an effective grating in the barium titanate crystal.

In contrast to this very broad spectrum Fig. 3(c) shows the relatively narrow spectrum of the mode-locked laser if the grating is grown following our DWP. This spectrum shows the well-known spectral narrowing property of the phase-conjugate mirror when the mirror is realized by a photorefractive

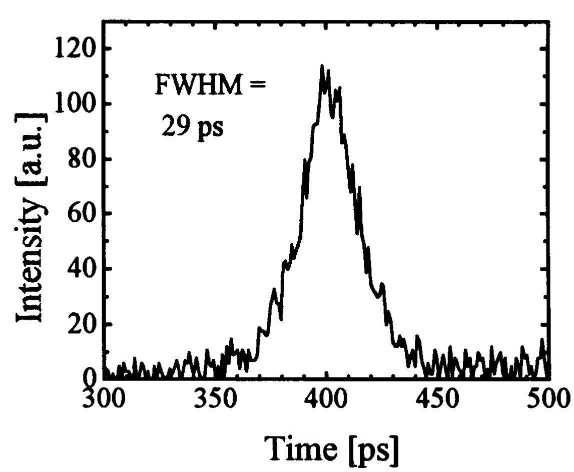


Fig. 2. Streak-camera trace of a 29-ps (FWHM) laser pulse with stable phase-conjugate feedback.

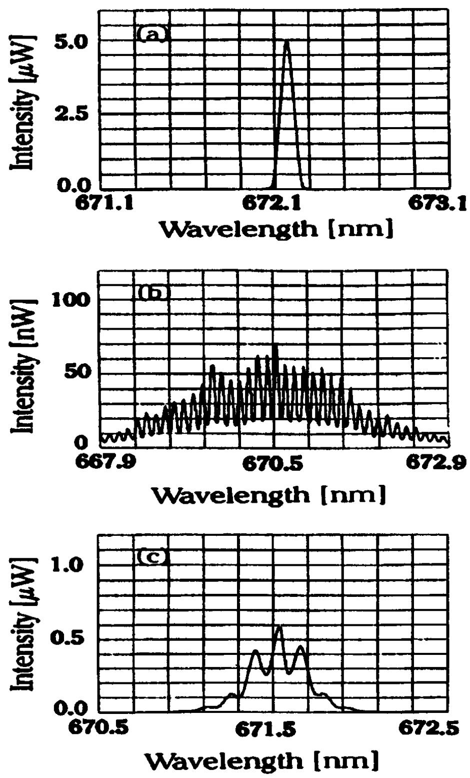


Fig. 3. Optical spectra of the diode laser: (a) dc injection current and phase-conjugate feedback, (b) laser mode locked to the conventional mirror cavity, (c) laser mode locked to the stable phase-conjugate mirror.

crystal.[10] The effect is similar to that of an external diffraction grating or an intracavity étalon. But, because of the phase-conjugate nature of the reflected light, the feedback efficiency is much higher than for those conventional optical narrowing techniques.

Finally, we demonstrate the high quality of the mode-locked pulse train obtained with the phase-conjugate mirror. We use the jitter analysis described by von der Linde[11] to evaluate the amplitude jitter and the timing jitter of the pulse train. This method investigates the dependence of pedestals on the order of harmonics in the intensity spectrum as measured by the rf spectrum analyzer. This evaluation indicates a 0.5% relative amplitude jitter and a less-than-2-ps timing jitter. These values are comparable with those that one obtains when operating with conventional feedback. On the other hand the same evaluation for the laser with feedback from a conventional grating shows higher values for the jitter because of the smaller amount of feedback from an external grating and shows clearly the superiority of the DWP over the approach of Segev *et al.*[7] We conclude from this that the stability of the pulse train with the long-term-stable phase-conjugate feedback is as good as that for conventional mirror feedback, and there is the advantage of a narrower optical spectrum without the disadvantages of lower feedback and higher jitter.

To summarize, we have described a new dynamical grating writing procedure that can be used to obtain long-term stable phase-conjugate feedback with photorefractive crystals for mode-locked semiconductor lasers. This is a first step toward practical applications inasmuch as we are combining the advantages of self-alignment and spectral narrowing of the phase-conjugate feedback with high-quality mode locking.

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