Beam coupling and locking of lasers using photorefractive four-wave mixing

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We discuss the use of photorefractive four-wave mixing for coupling and locking of lasers. A demonstration of the double phase-conjugate mirror and the semilinear passive phase-conjugate mirror, pumped simultaneously by different lasers, is described. Cleanup of a distorted laser beam using another local laser and configurations for the phase locking of lasers are discussed.

We present various four-wave mixing (4WM) configurations[1] for coherent beam combining, amplification, and cleanup as well as laser locking using photorefractive crystals. In these devices, as opposed to two-wave mixing schemes,[2] light feedback into the different lasers that are mutually pumping the 4WM process can cause beam combining and laser locking. Two 4WM configurations[1,3] were studied, the double phase-conjugate mirror (DPCM) and the semilinear passive phase-conjugate mirror (PPCM), shown schematically in Fig. 1.

We start with the operation of the DPCM using two separate lasers as inputs to the opposite sides of a $BaTiO_3$ crystal, as shown in Figs. 1(a) and 2. Laser 1 was a Spectra-Physics Model 165 argon-ion laser operating at its 488-nm line in multimode operation. It was situated in a different room from the crystal and from laser 2, at an optical path length greater than 10 m from the crystal. Beam 4 from this laser entered the $z = 0$ face of the crystal. Laser 2 was a Spectra-Physics Model 171 argon-ion laser, also operating in multimode at its 488-nm line. Beam 2 from this laser, which was situated on the same table as the crystal, entered the $z = l$ face of the same crystal after having traversed 1 m from the laser. The angles of the input beams, which were extraordinarily polarized, were similar to the semilinear PPCM configuration.[1] The two input beams were loosely focused by lenses 1 and 2, with a focal length of 15 cm, and overlapped in the crystal. We observed that these two independent inputs coupled into each other by mutually pumping a single, efficient 4WM process, resulting in the emergence of phase-conjugate output beams $A_1 \propto A^*_2$ and $A_3 \propto A^*_4$, where A_i are the complex amplitudes of the beams. We stress that, in this configuration, beam A_4 supplies the photons for beam A_1 and beam A_2 is the source of photons for beam A_3, so the two input beams are self-bent into each other. Care was taken to ensure that no internal-reflection mechanism nor a two-wave mixing process could form the phase conjugation. In this configuration, each of the input beams 2 and 4 forms its own writing mates 1 and 3, respectively. Thus, the beams have a minimal coherence requirement. In a former paper,[3] we analyzed and demonstrated the DPCM. Its transmission or self-bending efficiency $[A_1(l)/A_4(0) = A_3(0)/A_2(l)]$ approaches unity for high coupling efficiency and negligible absorption. This can lead to high reflection amplification $[A_1(l)/A_2(l)$ or $A_3(0)/A_4(0)]$.

The self-induced gratings and the passive buildup of the two output beams in the DPCM pumped with incoherent, separate lasers are possible even without an exact frequency matching of the pumps. The restriction on the maximum allowable difference in wavelengths $\Delta\lambda$ is dictated by the volume gratings' selectivity, $(\Delta\lambda/\lambda) \lesssim (\Lambda_g/l)f$, where Λ_g is the grating period, l is the interaction width in the crystal, and f is a geometric factor for the 4WM configuration.[4] Typical values of $l \sim 1$ mm and $\Lambda_g \sim 2$ μm give $\Delta\lambda \lesssim 1$ nm. We emphasize that the gratings' limited frequency response, which is of the order of 1 Hz for $BaTiO_3$, does not impose restrictions. Thus different frequencies of

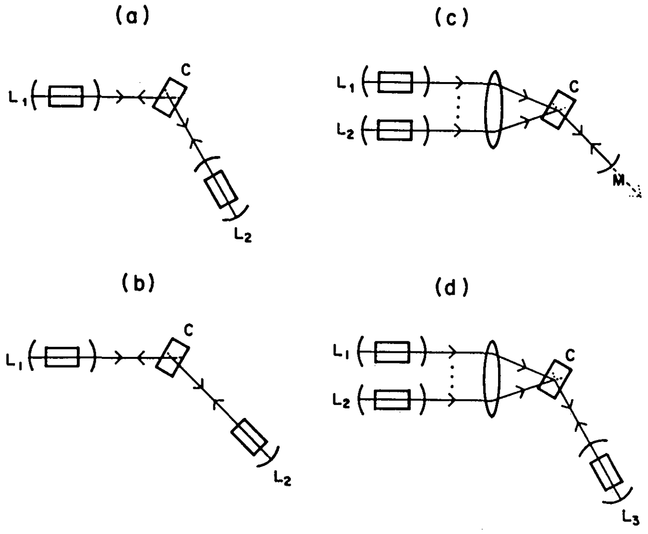

Fig. 1. 4WM schemes in a photorefractive crystal C for laser coupling: (a) the DPCM with two lasers, L_1 and L_2; (b) laser locking with coupled cavities using the DPCM; (c) semilinear PPCM with multiple inputs; (d) proposed multiple laser locking using the DPCM.

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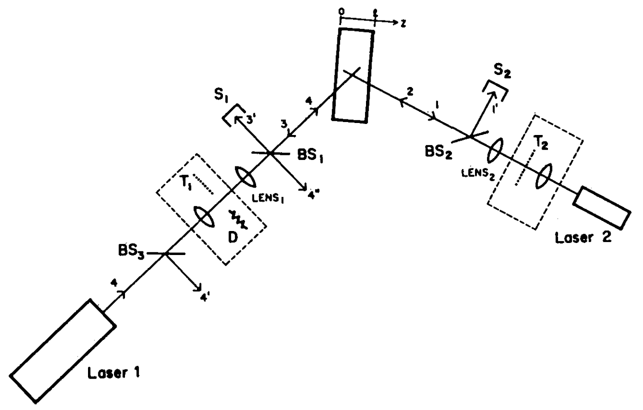


Fig. 2. Schematic of the two-laser-pumped DPCM. The boxed components were for the image-conjugation (including optics for beam expansion) or beam-cleanup experiments. BS's, beam splitter; D, distortion; LENS's, lenses used for focusing input beams 4 and 2 in the crystal, both with a focal length of 15 cm; S's, screens; T's, transparencies.

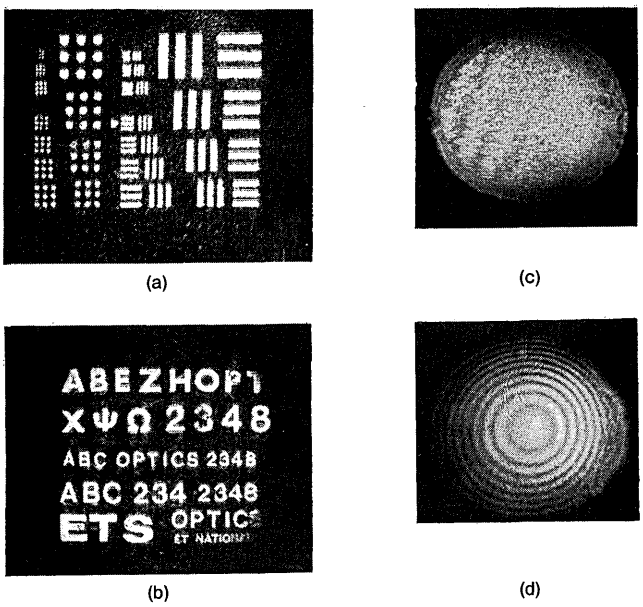
the same line of the argon-ion lasers for the two pumps are permissible.

The image-conjugating ability of this DPCM was tested by using two transparencies, as shown in Fig. 2. Slides T_1 and T_2 were simultaneously illuminated by expanded beams 4 and 2, respectively, which were then loosely focused in the crystal. The crystal was situated near the focal plane of lenses LENS$_1$ and LENS$_2$. The exact position of the slides between the beam-expanding optics and focusing lenses LENS$_1$ and LENS$_2$ was found to be insignificant. Portions of the phase-conjugate output beams $3'$ and $1'$ as seen simultaneously on screens S_1 and S_2, respectively, are shown in Figs. 3(a) and 3(b). High-quality images, as for the previously reported DPCM with one common laser input,[3] were obtained. As in previous work with the DPCM[3] and image-bearing photorefractive oscillators,[3,5] no intensity cross talk was observed. In the ring PPCM,[1] the oscillation also produces phase-conjugate counterpropagating beams, resulting in the maximum spatial overlap and gain in the photorefractive crystal.

Spatial phase aberrations in a laser beam can be cleaned up by using the undistorted beam from another local laser source. We investigated this capability by removing T_1 and T_2 and inserting a clear transparency smeared with Vaseline (D), which severely distorted input beam 4. The amount of distortion was checked by sampling beam 4 before the distortion (beam $4'$) and interferring it with a portion of the aberrated input $4''$, as shown in Fig. 3(c). An undistorted input beam 2 from laser 2 interacted with beam 4 in the crystal, so that a clean phase-conjugate output beam 1 emerged. An interferometric check of $1'$ with $4'$ revealed virtually aberration-free wave fronts, as shown in Fig. 3(d). This system, as opposed to another two-wave mixing device,[2] does not require coherent beams at the input.

We also studied the beam-combining capability of the multipumped semilinear PPCM shown in Fig. 1(c). Here a single oscillation between the crystal and the mirror M may build up owing to pumping with an array of lasers. This can result in beam combining in the common oscillating beam as well as phase locking of the laser array owing to phase-conjugate feedback of the 4WM process. An experimental evaluation of this scheme was carried out by using the two argon-ion lasers with beam intensities of 15 mW. Oscillation intensity in the crystal-mirror cavity (with mirror reflectivity of 0.7) due to the simultaneous pumping of the lasers typically exceeded by a factor of 3 the sum of the individual oscillation intensities for each laser operating separately. We noticed that even in cases when laser 2 was unable to build up a 4WM oscillation alone, laser 1 induced a coupled oscillation fed by both lasers, so that the phase conjugate of both lasers' beams still emerged. A detailed analysis of this system including the mutual interaction of the pumps is under way. Another configuration that could be used for beam combining is the multipumped unidirectional ring oscillator.[1]

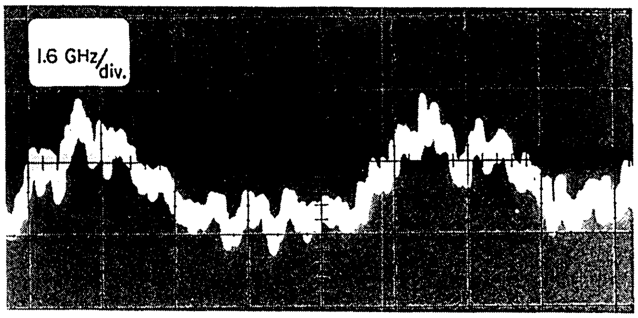
In these 4WM configurations, the beam-coupling mechanism adapts to inputs from different lasers and acts as a dynamic self-adjusted grating to channel energy from each laser into the other. This suggests its use for coherently combining and phase locking lasers,[6] as shown in Fig. 1. Phase locking of the two argon-ion lasers initially operating in multimode (without étalons) was studied in the DPCM scheme of Fig. 1(b). The output mirrors were removed from both lasers and replaced by a single variable beam splitter set at an intensity transmission of about 0.2 at the output of the laser 1 cavity. Here the cavities are



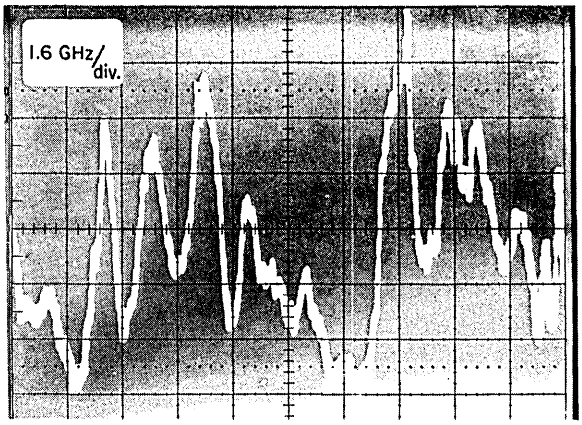
(a) (c)

(b) (d)

Fig. 3. Results of the phase-conjugation [(a), (b)] and beam-cleanup [(c), (d)] experiments with the two-laser-pumped DPCM of Fig. 2. (a) Phase-conjugate output of T_1 seen at S_1 and simultaneously; (b) phase-conjugate output of T_2 seen at S_2; (c) interferometric check of the input beam 4 distortion after passing through distorter D; (d) interferometric check of the undistorted phase fronts of output beam 1 due to beam cleanup by the DPCM.



(a)



(b)

Fig. 4. (a) Two successive scans of the laser L_2 spectrum [in Fig. 1(b)] with cavity-length detuning, measured with an 8-GHz free-spectral-range étalon at a scan rate of 500 Hz. (b) Spectra after cavity tuning displaying short-term phase locking. Note the change in the spectra for the two scans, as discussed in the text.

coupled to each other, permitting frequency selectivity for proper cavity lengths. Phase locking is possible for small-cavity detuning and depends on the energy coupling between the cavities.[7,8] We set up two cavities with lengths of approximately 1.3 and 13 m with an adjustable arm length of the longer laser 2 cavity using a sliding corner cube. The spectrum of laser 2 before tuning, measured with an 8-GHz free-spectral-range étalon at a scan rate of 500 Hz, is shown in Fig. 4(a). This spectrum was identical to that of laser 2 looking into free space. We observed that, with simple matching of the cavity lengths, without a change in the other parameters, the lasers oscillated in a few common modes owing to the frequency selectivity of the coupled cavities. The resulting spectrum, seen in Fig. 4(b), was observed to be stable for periods of the order of 1 msec. We emphasize that the lasers were neither externally stabilized nor isolated. Long-term locking is expected with stabilized lasers and shorter cavity lengths. Diode-laser locking should also prove to be simpler, given these lasers' easier line selection and control by way of the diode current and higher light coupling.[9] This will permit locking of laser arrays, as shown schematically in Figs. 1(c) and 1(d). We are currently investigating these topics.

We have demonstrated the operation of the DPCM and the semilinear PPCM pumped simultaneously by two different argon-ion lasers. Owing to the 4WM process, the pumping beams couple energy into each other and can cause beam combining and laser locking. We have demonstrated beam cleanup with the DPCM and beam combining with the semilinear PPCM. In addition, we have presented results showing short-term phase locking of the two argon ion lasers using the DPCM and have discussed configurations for the locking of laser arrays.

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