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Diode-Laser Phase Conjugation 03-FS-030 Final Report

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Diode Laser Phase Conjugation
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I. Introduction

Arrays of lasers are often considered when a need exists to increase laser optical output power, for a variety of purposes. Similarly, individual semiconductor laser-diodes, generating 0.01 – 1.0 W each, are commonly placed in arrays in order to increase total optical power onto targeted objects. Examples of such usage are diode-laser pump arrays for solid-slab heat-capacity lasers, laser arrays for heat-treating materials, and arrays for efficient solid state laser systems. The commercial and defense communities also use such arrays for many applications from laser range-finders, laser designators, to laser machining systems, etc. However, the arraying process does not automatically increase "focusable" light on target (i.e., intensity/steradian).

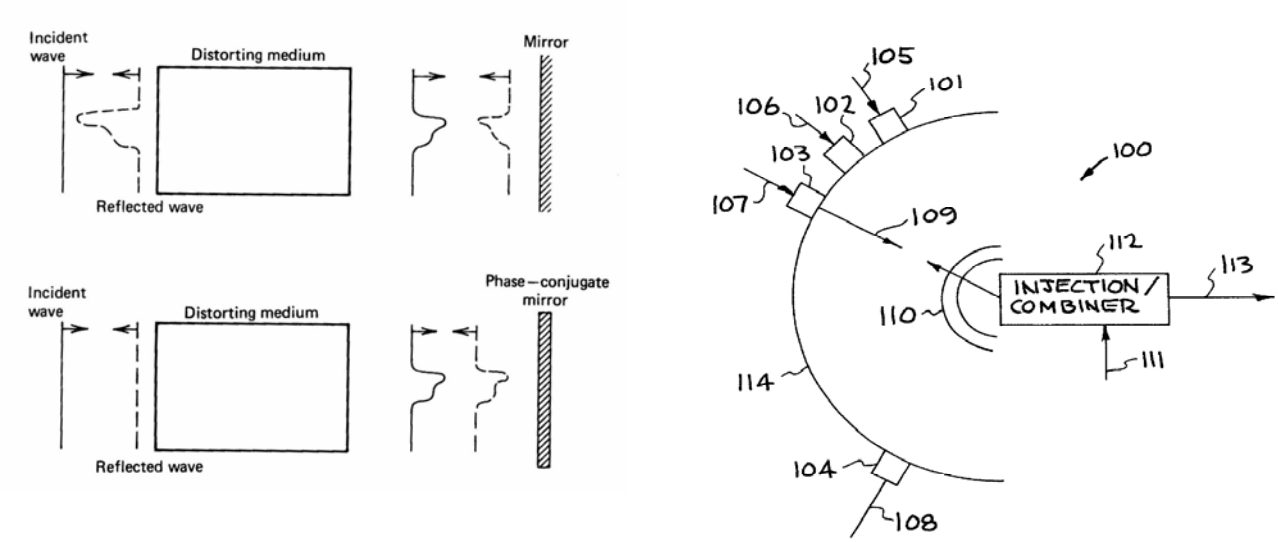
For those applications requiring the highest focusability, it is necessary that the collective output beam from arrays of individual lasers be phase-coherent. Under this condition, the individual laser-element optical outputs are "fused together" into a larger area, phase coherent (i.e., all wavefronts are "in step"), high-power combined beam. The process of joining multiple laser beams together to produce a single coherent wave, is in general very difficult and seldom accomplished. Thus joining together many hundreds to thousands of beams from individual laser-diodes, in large arrays, is still an unsolved problem. There are 2 major reasons for this.

Firstly, the phase of each output laser beam (i.e. the wave-fronts) from each laser diode often fluctuates within nanosecond time periods, making a control loop with sufficient bandwidth difficult to build. In fact, phase fluctuations (related to laser linewidth) limit the size of an extended system of arrayed diodes because of speed-of-light restrictions on information flow. Secondly, the output power per prior laser diode has been low (< 1W,) so that the size, expense, and complexity of control systems for correcting a multitude of output phases of the individual diode lasers in a large array, become prohibitive.

Recently, we have been considering ways to use new diode geometries and 4-wave mixing/phase-conjugation technologies to enable large arrays of semiconductor lasers to be phased together to produce large-output-power laser systems, with good beam quality. If the ideas hold up, arrays of 100 to > 1 million laser elements might produce 100 W to > 1 Megawatt laser beams. Such systems can have many defense and commercial applications.

II. Phase-conjugation might enable phasing of arrays

Although a variety of laser-phase-locking schemes have been modeled and/or tested, so far none has been well-proven. An alternative approach is use nonlinear-optical effects to automatically take care of the phasing, instead of attempting to use electro-optic phase adjusters or optical coupling between a multitude of oscillators. A design concept is illustrated in Figure 1.



(a) (b)

Fig. 1. Conceptual diagram of phase-conjugation technique for generating phase-coherent array. (a) A phase-conjugate mirror retro-reflects an input waveform with good fidelity (and in some instances, gain.) The phase-conjugate mirror could be sectioned into small pieces, enabling assembly of an array. Lumped into the block "distorting medium" are individual "piston" errors and various other wavefront aberrations. (b) [after Holzrichter and Ruggiero, US Patent 6693943] An oscillator signal ***110*** is fanned out to a multitude of phase-conjugating laser elements ***101 – 104*** that amplify and retro-reflect it. Because the return signals are conjugate waves, the round-trip phase is identical for each path. A Faraday element ***112*** is used to separate the counterpropagating coherent-array signal from the oscillator input. Frequency locking of the various phase conjugators is furnished via connections ***105 – 108***.

In a simple model of phase conjugation, [1] an incoming beam (from an oscillator in this case) interferes with a ("forward-going," for the sake of argument) pump laser beam inside a polarizable medium (in this case, laser gain material.) Intensity fringes from the superposed waves modulate the gain-medium's inversion density and/or refractive index, writing a "grating." The fringe pattern's position in space automatically responds to changes in the arrival time (phase) of the incoming beam. The "backward-going" pump laser beam (opposite in direction to the forward-going beam, and at the same optical frequency) polarizes the "grating," causing radiation of a phase-conjugate wave that retraces the incoming beam's path. It can be shown that the round-trip phase in this arrangement is independent of the position of the conjugating laser element, and of distortions introduced into the optical path. In that sense, the scheme of Fig. 1 resembles an aberration-corrector that has been sectioned into many small pieces. [1]

To be useful, each "laser element" in Figure 1 should produce a phase-conjugated beam that is (a) more powerful than the incoming oscillator beam, and (b) at nearly the same optical frequency as the beam from every other laser element. Due to the four-wave-mixing nature of this phase-conjugation scheme, with an input (reference beam) at frequency ν_r, the conjugate beam from laser element ***n*** (containing pump field at ν_p^n) is at optical frequency

$$\nu_{PC}^{n} = 2\nu_{p}^{n} - \nu_{r}$$

To avoid wide dispersion of the conjugate frequencies, and consequent loss of coherence, careful frequency control of each laser element is mandated. It is difficult to make an assembly of lasers run at the same frequency (to within 1 GHz or so,) but a notional scheme (shown in Figure 2) is to use injection-locking with a single master oscillator. (Since each laser element can have an arbitrary phase, this is considered easier than direct phase-locking of an entire array.)

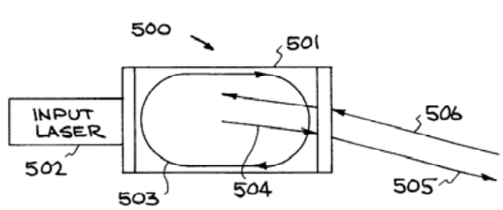


Fig. 2. [after Holzrichter and Ruggiero, US Patent 6693943] Typical phase-conjugation concept using an input fiber ***502*** to frequency-lock the internal circulating laser wave ***503,*** (i.e. the "pump wave") inside the [diode] laser cavity.

III. Semiconductors are attractive for phase conjugation

In principle, all laser gain media have nonzero third-order nonlinear-optical susceptibilities (i.e., can be saturated and will exhibit phase-conjugation,) so there are many choices for the "laser elements" of Figures 1 and 2. Semiconductor lasers are attractive for a variety of reasons:

- Low cost, easily mass-produced
- Fast (nanosecond) time response
- High electrical-to-optical efficiency
- High brightness
- High gain per pass

- Large third-order susceptibility (strong conjugator)

The greatly-enhanced nonlinear response (traceable directly to the band structure of semiconductors) is associated with the "linewidth-enhancement factor" β, that relates variations of the real and imaginary parts of the linear susceptibility. Basically, saturation-induced modulation of the inversion (and gain coefficient) causes a modulation of the polarizability that is β times larger. The overall four-wave-mixing (phase conjugation) response varies as $(1 + \beta^2;)$ for semiconductors, $\beta \sim 5$, whereas for other lasers (rare earth ions, gas atoms, molecules) $\beta \sim 0$. [2] So, semiconductors are about 25 times better for phase conjugation.

The dramatic four-wave-mixing properties of semiconductors are of theoretical as well as widespread practical interest (for frequency conversion in telecommunications.) Use of semiconductor diode laser media for phase conjugation has been studied by many investigators. [3] Early work has been done by Amnon Yariv at Cal Tech, Jack Feinberg at USC, and many Japanese investigators. Notably, Govind Agrawal (formerly of Bell Labs, and now at the University of Rochester) published a widely-cited model. [4]

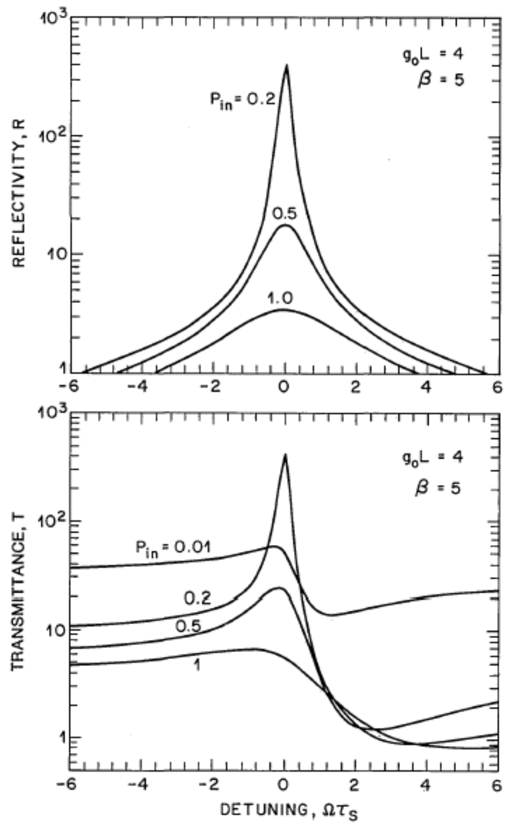


Fig. 3 (after Agrawal [4].) Variation of the conjugate reflectivity R and the probe transmittance T with the normalized pump-probe detuning $\Omega\tau_S$, for several incident pump intensities when the semiconductor laser operates as a traveling-wave amplifier with $g_0L = 4$.

Key results of this model are shown in Figure 3, pertaining to a high-gain amplifier in which the "pump" and "signal" waves are introduced with a (dimensionless) detuning $\Omega\tau_s$. (Here τ_s is the carrier lifetime ~ 1 nanosecond.) The gain (in the absence of saturation) is g_0L nepers, but is reduced upon introduction of a pump signal P_{in} (in units of the saturation power.) The top portion of the figure attracted our attention; note that phase-conjugation gains ostensibly range from a few, to a few hundred. Because the interacting and phase-conjugated waves are amplified while traversing the amplifier, its gain dramatically affects the overall phase-conjugating reflectivity. So, there is a tradeoff between using high pump power (to make a strong nonlinear polarization) and maintaining high amplifier gain. Thus, optimization of mixing efficiency has recently been a topic of interest. [5] There has also been a series of papers [6] from Kerry Vahala's group about a decade ago, mapping out the mixing-efficiency behavior of fiber-coupled, single-mode semiconductor amplifiers.

IV. Broad-area diode experimental setup

We began to investigate the prospects for using broad-area diodes as phase conjugators in the Figure 1 scheme, since they offer reasonable output power per aperture, and can be comparatively-densely packed in an array. Although we tried various experimental setups, a representative one is shown in Figure 4.

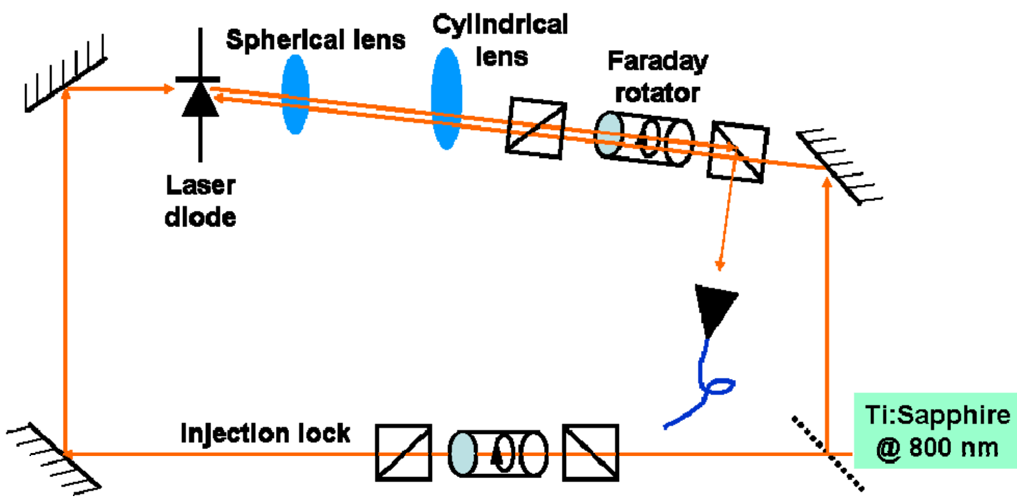


Fig. 4. Setup for measuring phase-conjugation in off-the-shelf broad-area diode lasers. In this example, the degenerate-frequency four-wave-mixing case is studied by using a single laser for injection-locking and for probing. The Ti:Sapphire laser must be tuned within the ~1 GHz locking range of the laser diode, and spatial mode-matching is also required for useful phase conjugation. For stability, the diode must be isolated from reflections, hence the use of Faraday isolators.

We obtained some standard broad-area diode lasers of ~1 W nominal output power, and output wavelength near 800 nm. Their 1 x 100 μm facet size and large beam divergences mandate use of special, cylindrical optics for beam formatting. Also, since semiconductor lasers are sensitive to back-reflection, Faraday isolators are used. A tunable Ti:sapphire laser provides narrowband light coincident with the diode's output wavelength. In general, the goal of an experiment would be to generate a set of curves along the lines of those in Figure 3, and also to measure the phase-conjugate beam quality. We would also want to vary parameters like the angle of incidence of the probe beam.

V. Laboratory results

Recognizing the need for good isolation of the laser diode, we had a series of 4 Faraday rotators re-coated to reduce reflections and improve extinction. The isolators were tuned by varying the length of crystal penetrating into the magnetic-field region. A plot of the measured extinction vs wavelength after such alignment is shown in Figure 5. The 30+ db extinction over the range of diode-laser wavelengths from 800 – 810 nm is adequate, but not exceptional.

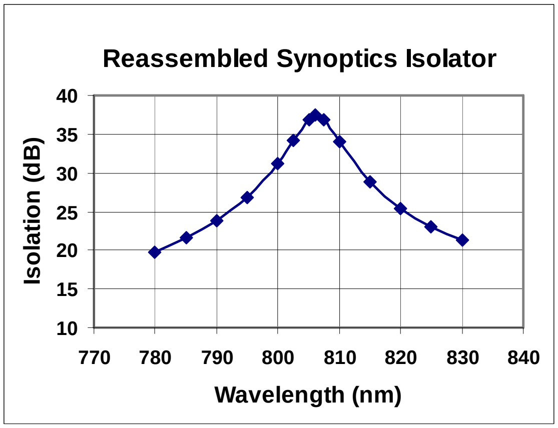
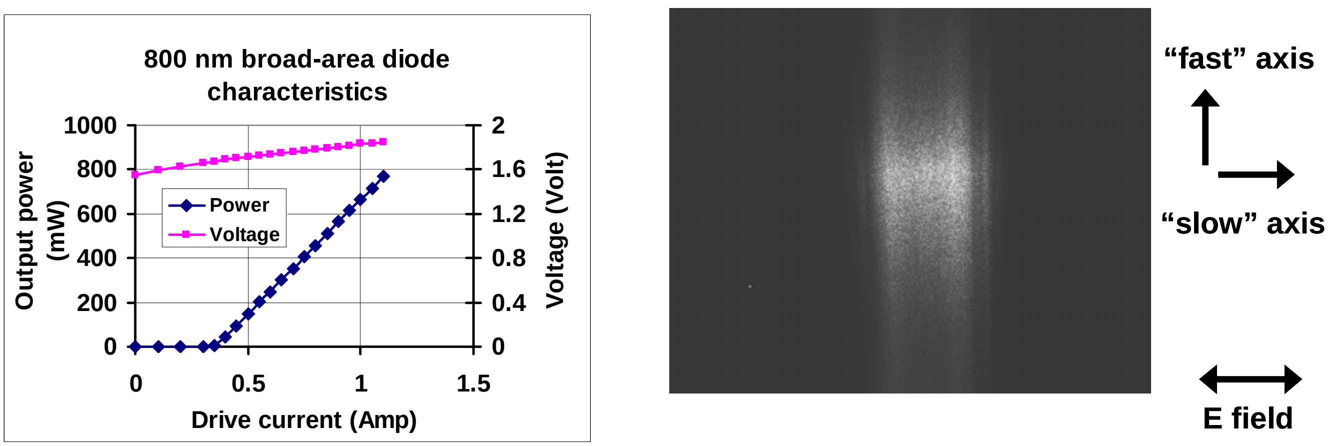


Figure 5. Measured isolation vs wavelength for one of the Faraday isolators we reworked and realigned.

We received a pair of broad-area laser diodes designed to work near 800 nm. Their nominal output power of 1 W and facet dimensions of 1 x 100 μm were considered "generic," and suitable for our experiments. Results of routine



(a) (b)

Figure 6. (a) Slope plot for broad-area diode. (b) Photograph of output spot with laser free-running. Vertical stripes are due to multiple-mode oscillation.

characterization are shown in Figure 6. The spatial mode (Fig. 6(b)) is as expected—fast divergence in the "fast" axis, with a smooth tapering-off of intensity corresponding to a Gaussian-like distribution; slow divergence in the "slow" axis, with multimode structure evident and abrupt edges. For most purposes, it is necessary to perform imaging and polarization control to take into account the diode's facet dimensions, beam divergences, and electric-field polarization.

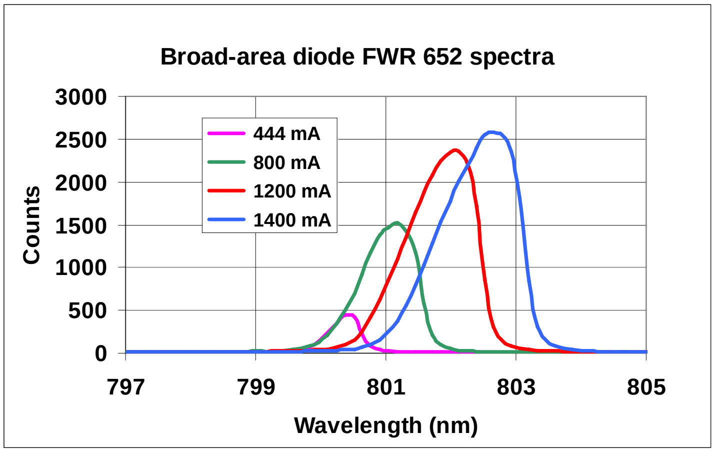
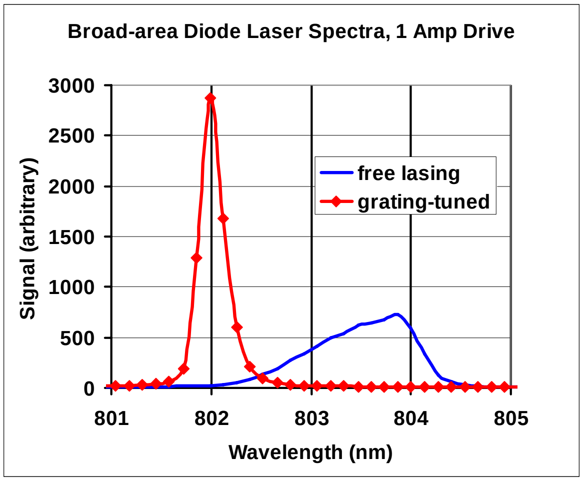


Figure 7. Spectra (at 0.3 nm resolution) of a broad-area diode at different operating points. Large shifts with operating current (probably due to diode temperature changes) are observed. For reference, 1 nm ~ 470 GHz.

Diode emission spectra are shown in Figure 7. The "C-mounted" diode was attached to a copper block, but did not have active temperature control at the time the data was taken. Large shifts with drive current are observed, and we presume that they are merely due to the normal 0.25 nm/C temperature drift characteristic of such laser diodes.

The frequency range over which efficient four-wave mixing occurs is roughly 1 GHz (an inverse carrier lifetime) either side of the laser's center frequency. (Wider frequency separations have been explored, especially for telecommunications, but the efficiency drops rapidly.) To frequency-resolve the four-wave-mixing signals from the laser and probe waves, narrow linewidths well below 1 GHz are thus helpful. (In the usual case where the return signal is weak, it is generally hard to achieve a good signal-to-noise ratio without modulating or chopping the input waves.)

One technique we used for line-narrowing was to install a grazing-incidence diffraction grating as part of an external cavity. This configuration had the advantage of simplicity, since no external beams had to be aligned or imaged onto the diode facet. Figure 8(a) shows the resulting spectra with the diode grating-tuned and free-running. For the purposes of the low-resolution spectrometer we used, the diffraction grating gave nearly an "instrument-limited" spectrum. Checks with a high-resolution scanning Fabry-Perot interferometer (not shown) showed that the spectrum had not collapsed into a single line, but contained a series of features. Since the diode did not have its front facet AR-coated, it is likely that multiple-cavity resonances affected the spectrum.



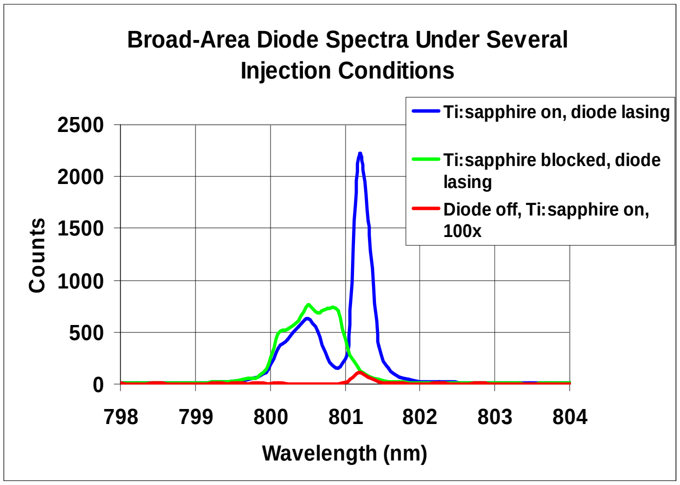


Figure 8(a). Spectral results for diode laser running with and without an external-grating tuner. Individual data points reflect the spectrometer pixel spacing (resolution.) (b) Results of injection-locking the diode laser. The injected signal (from the Ti:sapphire laser) captured ~2/3 of the diode emission.

We hoped that injection-locking would provide better frequency control of the diode laser, since the Ti:sapphire laser spectrum is extremely narrow. The locking beam was introduced through some imaging optics, off-axis. It proved difficult to achieve locking, since alignment was difficult and the diode laser's locking range is only ~1 GHz, according to standard theories. Small temperature drifts (~0.01 C) would be enough to detune the locking resonance. In spite of that, the result of Figure 8(b) was achieved—roughly 2/3 of the diode emission captured. Not that the leaked locking-signal strength (red curve) has been amplified by 100.

VI. Challenges associated with diode-laser phase conjugation

A significant portion of our work has been devoted to studying literature and becoming familiar with the challenges of diode-laser deployment. Frequency control (by injection locking and with external-cavity resonators,) mode matching, temperature stabilization, and spatial mode control have all been topics of interest.

We note that a few (not many) other workers have also researched phase conjugation in broad-area diodes. [7] Conversion efficiencies (gains) of a few dB have been reported, but so far, curves like those in Fig. 3 have not appeared in the literature. So, the limits of performace of broad-area diodes as phase conjugators have probably still not been stringently tested. (An over-arching concern in this area is the difficulty of achieving single-mode operation so as to make a "clean" comparison with expectations. Overlap factors etc. are difficult to quantify in multi-mode situations.) At this point, we believe we have "framed the problem."

Overall, there are many reasons to challenge the practicality of the scheme *in semiconductor laser systems*, see in Figure 1:

1. The four-wave-mixing conversion efficiency is limited by the overall gain of the laser (or amplifier,) circulating intensity, and value of the nonlinear susceptibility.   The value of interest is approximately $(X^{(3)} \bullet G \bullet I_{circ})^2$. Note that in figure 3, the single-pass gain $\mathbf{g_0 L}$ of 4 neper is very large—around 500. An operating laser would not have such a high gain, and an amplifier operating with a high circulating intensity would also have its gain reduced by saturation. Credible conversion gains have probably not been observed. If they had, the four-wave-mixing (intermodulation) products would be as strong as the pump ("carrier") field, and higher-order signals (intermodulation products) would also be observed—six-wave-mixing, etc. (This would be of high interest in the telecommunications field.) Only near semiconductor damage thresholds (plasma formation) have such effects been noted.

2. The nonlinearity (modulation of the refractive index by local intensity changes) giving rise to the strong four-wave-mixing / phase-conjugation effect also acts to destabilize the diode laser. Feedback effects, filamentation that degrades the spatial mode, shifts in operating point with power level, etc. tend to plague diode lasers.

3. The small detuning (~1 GHz) over which the 4WM is maximized is not sufficient to extract a phase-conjugate beam conveniently. Even though 1 GHz is a high frequency, it is only ~ 2 parts per million of the optical frequency. High-resolution spectroscopic techniques are normally required to separate signals with this sort of frequency difference.

4. Mode-matching to broad-area-diode facets is challenging. Imperfect launching into, and collection of light from, a 1 x 100 μm (or similar) facet will degrade efficiency.

5. Diffraction may degrade the phase-conjugate beam. Intensity ripple across a multimode-diode facet will be impressed on the 4WM signal as well—some locations will conjugate better than others because the circulating field is stronger. This ripple will lead to diffraction and beam spreading.

6. Tight temperature control (~0.01 C) is needed to keep a diode laser fixed on a certain frequency within 1 GHz. While not impossible, this is difficult for a single diode, and much more difficult for a large array.

VII. Possibilies with "α-DFB" (angled-grating) lasers

To increase the likelyhood of the Fig. 1 scheme for coherent-light generation, phase conjugation with good gain and good beam quality must still be demonstrated.   To "close the loop" we would need not only to measure the phase-conjugation signal strength and mode pattern, but also characterize the diodes' microscopic properties (carrier lifetime and saturation intensity, for example.) It is important to work on semiconductor modules that are configured both as amplifiers (i.e. with AR-coated facets) and as lasers.

Given our work to date in this field, we recognize that standard broad-area-diodes have shortcomings intimately related to the strong connection between gain and refractive-index perturbations. In other words, the phenomenon that makes diodes strong phase-conjugators, also creates other problems—filamentation and multimode operation, for example. The challenge of obtaining single-mode (in space and in frequency) operation is significant, even for a single diode laser, and probably more difficult if a multitude of diodes is involved. So, we are motivated to check out a system (Figure 9) in which transverse-mode selection is built in—the so-called "angled-grating" lasers. [8] When the light reflects off the angled gratings, the high-order modes experience much-larger loss and are suppressed. When configured with DFB end-mirror structures, angled-grating lasers can exhibit narrow linewidths below 1 GHz, suitable for phase-conjugation work. Furthermore, the "M squared" value can be a small number (below ~3.) [9] In each of these two respects, the angled-grating systems are orders of magnitude better than standard broad-area diodes.

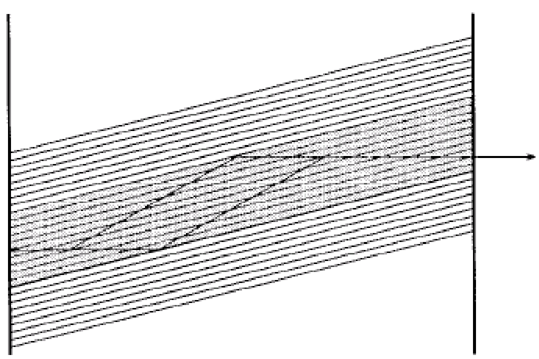


Fig. 9 (after Lang [8]) Schematic diagram of angled-grating laser with standard end mirrors. The internal grating selects both the frequency and angle of propagation of the resonant modes. Near-single-mode operation is possible with such diode-laser architectures.

VIII. Conclusion

We have critically examined a proposed scheme for power-scaling an array of broad-area diode lasers using a four-wave-mixing / phase-conjugation technique. In doing so, we have surveyed the relevant literature, consulted experts, and attempted laboratory experiments. The scheme does not appear practical with presently-available diode lasers. However, use of angled-grating diode lasers may mitigate some of the challenges.

The importance of solving the large area, high brightness laser problem continues. Large high power, high brightness lasers are not available today, and attempts using gaseous systems, such as the airborne laser system, are running into many problems. While the use of diode laser arrays to enable this concept appears unmanageable at this time, the general concept could be explored further using other configurations of gain, non-linear element, gratings, etc. The general

LLNL invented concepts behind large area, coherent arrays might still be physically realizable.

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