Preliminary Results Toward Injection Locking of an Incoherent Laser Array

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The preliminary results of phase-locking an incoherent laser array to a master source in an attempt to achieve coherent operation are presented. The techniques necessary to demonstrate phase-locking are described along with some topics for future consideration. As expected, the results obtained suggest that injection locking of an array, where the spacing between adjacent longitudinal modes of its elements is significantly larger than the locking bandwidth, may not be feasible.

I. Introduction

Recently, a project was initiated to determine the ease and feasibility of injection locking an incoherent laser diode array. Previous experimental work directly related to this task consisted of the injection locking of a coherent phase-coupled array (Ref. 1) and the locking of single and multiple slave laser diodes to a master oscillator. In the former case, one is interested in transforming the stable 180° out-of-phase operation of adjacent lasers, which results in a two-lobed far field pattern, to that of in-phase operation leading to a single lobed far field. In the cases of single (Refs. 2, 3) and multiple (Ref. 4) slaves, locking of both frequency and relative phase was accomplished. Each of these activities is a natural precursor to the current aim, though none have been as demanding in the nature of the interaction between the master and slave lasers. Before discussing the goals of the present experiment, it will be helpful to briefly review the accomplishments of previous work done in this area.

The work undertaken by Kobayaski and Kimura was to demonstrate the applicability of the theoretical injection locking model of Adler (Ref. 5) to semiconductor injection lasers. Earlier, experimental results supporting Adler's theory had been obtained using He-Ne lasers by Stover and Steier (Ref. 6), but no such results had been obtained for semiconductor lasers. Adler's model was developed for the case of a general oscillator and has been extended by Lang (Ref. 7) to the specific problems of injection lasers whose index of refraction is carrier-density dependent. Kobayaski and Kimura found that the locking bandwidth is 3 GHz (0.1 Å) when the injection locking gain is 23 dB and 500 MHz at 40 dB gain. These values agree well with those predicted by Adler's theory.

The first multi-slave laser locking results were obtained by Goldberg, et al. (Ref. 1), on the locking of four single diode lasers to a master laser. They measured a locking bandwidth of 3 GHz using an injected input of 100 μW and a slave output of 5 mW (17 dB gain). They also reported that they could force the laser to oscillate 22 modes away from its free running mode with a single laser output of 3 mW and an injected power of 40 μW (19 dB gain). Goldberg, et al., was also the

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first group to use injection locking techniques on a laser array. Their phase coupled array was successfully converted to single lobe operation and the spectral width was slightly narrowed.

Laboratory set-ups for all of the prior experiments have been of a design (Fig. 1) similar to that used for the present measurements. A few of the differences are as follows:

(1) Prior experiments have utilized Fabry-Perot interferometers to achieve a finer resolution often needed to determine the locking bandwidth (typically 0.1 Å). The present experiment did not seek a quantitative measure of the bandwidth but only a demonstration that locking could be achieved.

(2) An optical isolator was used in previous experiments to shield the master laser from influences of the slave laser. Optical feedback can manifest itself in two ways (Ref. 8):

   (a) Radiation from the slave may enter the master causing a frequency push/pull battle, or

   (b) Reflected radiation from the injected facet of the slave may induce instability and mode break up in the master. These problems were minimized by injecting off axis although coupling efficiency was sacrificed.

II. Description of Apparatus

The master laser, a Mitsubishi ML 3101, was focused onto the back facet of the slave array using a 10X, numerical aperture 0.30 microscope objective. The object distance was 3 mm with an image distance of 495 mm resulting in an image size at the back facet of the array of 1,500 μm^2. The output of the array was then imaged onto the screen of a vidicon placed 21 cm away using another 10X objective to obtain the near field pattern. This leg of the beam path was sent through a beam splitter and a portion of the beam was focused into a monochrometer placed 76 cm away using a 1-in. diameter, $f = 100$ mm lens. Placed before the monochrometer was a dove prism to rotate the horizontally separate spatial modes of the array into the vertical plane, allowing the imaging of the spatial and temporal modes simultaneously.

The slave laser array used was an index-guided, 10 element incoherent laser array obtained from Ortel Corporation with a threshold current of 175 milliamps (Fig. 2) and which emits equal power levels from both front and rear facets. The maximum current limit was presumed to be around 450 milliamps and care was taken not to exceed this limit. The intensities of the individual elements were quite uneven (Fig. 3) as were the center frequencies and the number of lasing modes (Fig. 4). Throughout the experiment the laser was normally operated at 275 milliamps peak current with a 5 kHz repetition rate and 0.22 μsec pulse width. The power emitted in each mode under these conditions is listed in the matrix of Table 1. The spectrum of the array is centered around 8518 Å. The master laser used in this experiment had a wavelength of 8529 Å at 25 milliamps and 8550 Å at 50 milliamps. No locking was seen (as was expected) at these wavelengths and power levels. A thermo-electric heater/cooler was attached to the array's heatsink to raise the operating temperature, and resulted in a shift of the resonances to longer wavelengths. GaAlAs lasers typically display a shift of 3Å/K. Coarse tuning of the master and slave laser frequencies was usually accomplished by controlling the temperature of the heatsinks on which the lasers were mounted and fine control was achieved by varying the current injected into the lasers. Unfortunately, at these higher temperatures the array exhibited a spreading of the gain profile, giving rise to many more lasing modes (Fig. 5).

III. Theory

Locking (Ref. 9) is predicted to occur when the power injected into a laser cavity and the cavity gain at that injected frequency exceed the gain of the free running natural frequency (Fig. 6). From Adler's theory, the approximate locking bandwidth is described by:

$$\Delta f = \left(\frac{f_o}{2Q}\right) \sqrt{\frac{P_{in}}{P_{osc}}} \qquad (1)$$

where P_{in} and P_{osc} are the powers of the injected laser and locked laser power, respectively, inside the oscillator, f_o is the center frequency and Q is the cavity Q of the slave given by:

$$Q = \omega_0 T_P$$

$$T_P = \text{photon lifetime} \qquad (2)$$

The measured average spacing of the cavity modes of the laser array was 2.7 Å. From this a cavity length of 400 μm was determined assuming a reflection coefficient of 0.32 and refractive index of 3.6. The resulting cavity Q was 6176. This is only an approximate analysis. A more precise formulation done by Lang has determined that the locking curve has a very asymmetric shape. Lang has found that locking is easier to a mode which is below the resonant frequency rather than above because of the carrier-density dependence of the index of refraction. More recent results indicate a more complicated behavior than predicted by Eq. (1) or Lang's calculations.

IV. Procedure and Results

The initial laser locking trials were carried out with the master driven at the same pulse repetition rate as the array but with a slightly longer pulse width of 0.5 μsec. The master and slave both support horizontally polarized light and were positioned to emit this polarization to optimize coupling. The array was heated to emit wavelengths in the region of the master. About 8% of the energy radiated by the master was actually incident on the facet of the array. This gives rise to approximately 8.2 μW of power actually coupled into each element of the slave array. A typical element of the array (No. 3, for example) emits 1.3 mW. This yields a locking bandwidth of 3.9 GHz with a 22 dB gain. As the two lasers were brought into synchronization, some of the lower power elements were noticeably shifted by as many as four modes (Fig. 7). The master could be tuned, using the current, to a point where a maximum of four (numbers 2, 3, 4, and 6) out of the ten elements showed signs of locking simultaneously. The energy in the wings of the beam footprint may have been too low to exert influence on elements 1 and 10 together with 2, 3, 4, and 6. Elements 1–4, 6, and 10 all showed some measure of locking at one time or another during the demonstration. No discernible change could be seen in the stronger elements 5, 7, 8, and 9. This may have been a result of the narrow gain profiles of these elements and low power injected from the master. As the power of the master laser was increased, its nearly single mode operation became predominately multimode, making the detection of frequency locking difficult.

Often when a laser is locked to a particular mode determined by the master, it does not necessarily operate in a single longitudinal mode. Injecting may create an unusual two-lobed gain profile. This problem seems to be more common in lasers with a narrow free-running gain profile than those with broad gain. Possibly, with higher injected power levels, the gain in the injected mode may be large enough to dominate the available population inversion initiating single mode operation. Figure 7 does show that for a low power element, the frequency spectrum can be dominated by the master effecting single mode operation.

Considering the nominal locking bandwidth (typically 0.1 Å), it is possible in an incoherent array with mode spacings on the order of 3 Å that if the elements have cavity resonances which are further apart than ~0.3 Å from each other, it may not be possible to lock an array. Careful measurements of the longitudinal modes should be made with a Fabry-Perot interferometer to determine if a problem along this line actually exists.

V. Future Considerations

One of the most serious drawbacks of the present attempt has been the low powers actually injected into the slave laser. The bulk of the problem should be correctable by using a different set of optics and using a cylindrical lens to achieve a footprint commensurate with the shape of the array. Another approach may be to use a higher power laser diode. A combination of both of these may be appropriate.

The critical need for an isolator was not readily apparent during these trials. The multimode behavior of the master laser was attributed to high injection current levels instead of optical feedback. Perhaps with the use of a Fabry-Perot interferometer and with more exact measurements, the presence of small frequency instabilities (~500 MHz) will be found to be much more bothersome.

VI. Conclusion

We have shown that the injection locking of an incoherent laser array is feasible provided the cavity modes of all elements of the slave device are within the locking bandwidth of each other. It was also shown that the lower power elements are more easily influenced and locked by the master laser than the higher power ones. Both of these results are in agreement with theoretical models of injection locking of semiconductor lasers. Further work should determine the characteristics of the far field profile and its usefulness for communication purposes.

Acknowledgment

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Table 1. Power vs mode matrix

Element	Mode Power, 10^{-3} W							
1					0.02		0.05	
2	0.02	0.07	0.07	0.07	0.14	0.07	0.05	0.02
3			0.05	0.19	0.56	0.38	0.05	
4		0.05	0.19	0.56	0.75	0.09*		
5	0.09	0.19	0.28	0.38	0.75	0.38	0.05	
6		0.19	0.70	0.75	0.09			
7			0.05	0.19	0.75	0.84	0.75	0.09
8		0.05	0.28	0.75	0.84	0.75	0.33	0.05
9	0.05	0.19	0.70	0.75	0.14	0.05		
10				0.09	0.14			

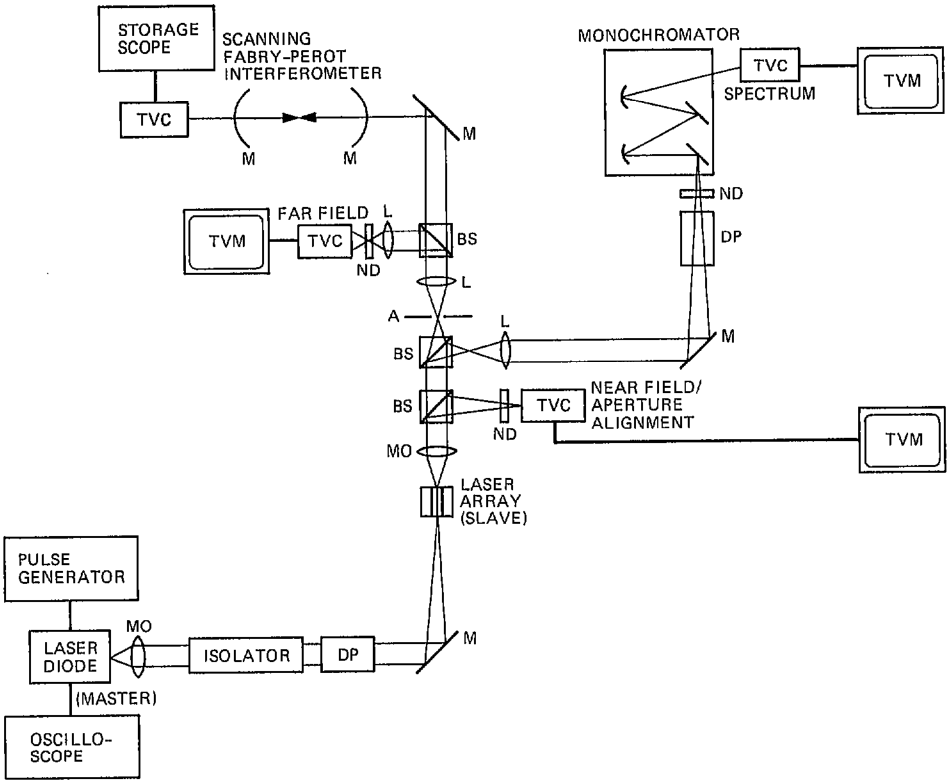

Fig. 1. Optical set-up used for injection locking

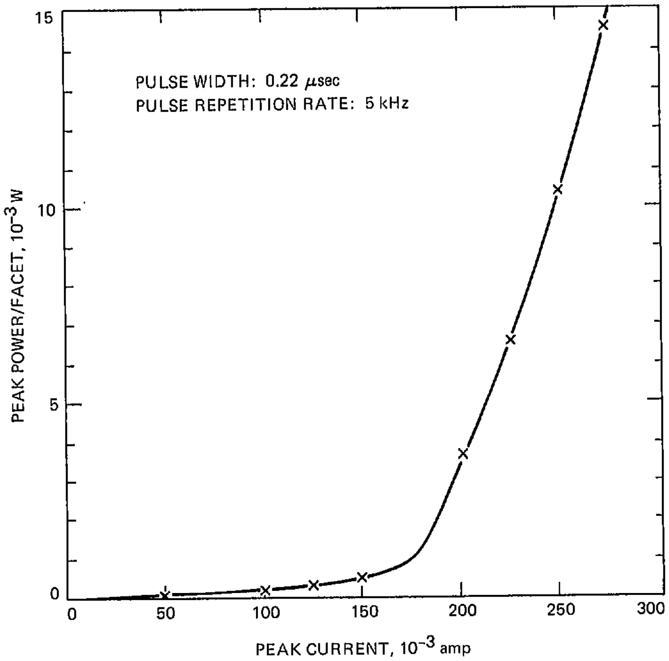

Fig. 2. Power vs injected current for array

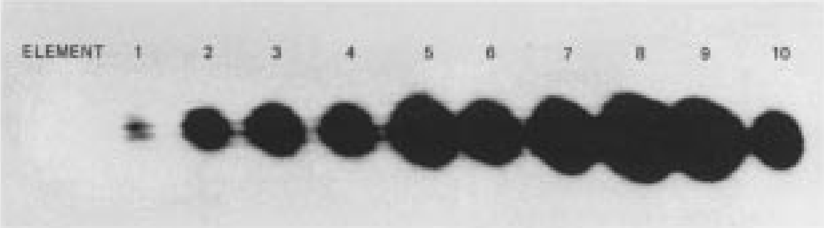

Fig. 3. Amplitude profile of array

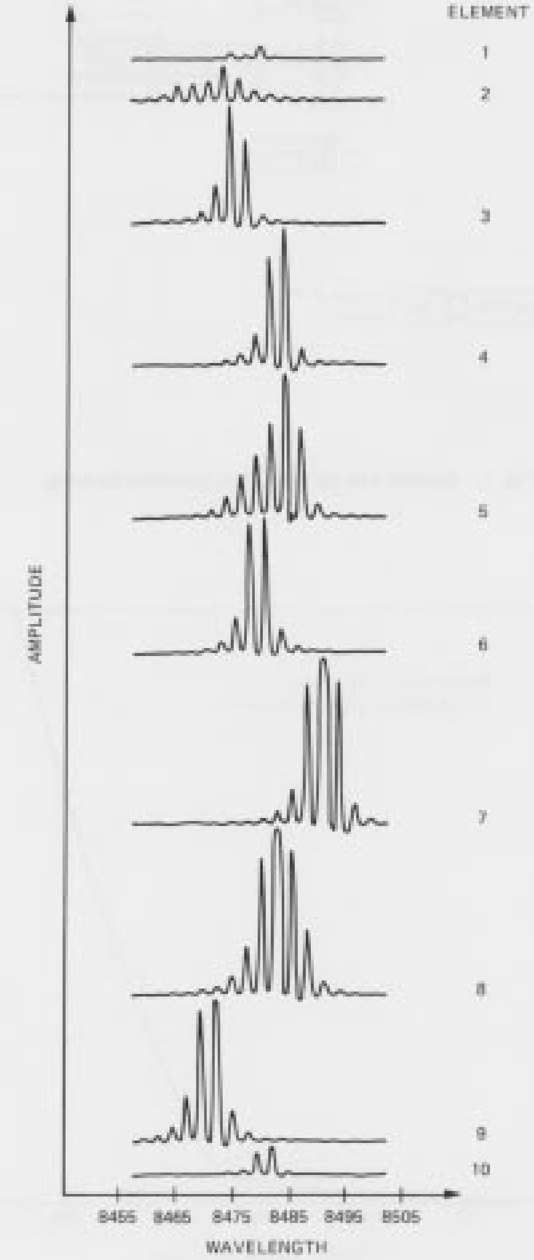

Fig. 4. Frequency spectrum of array

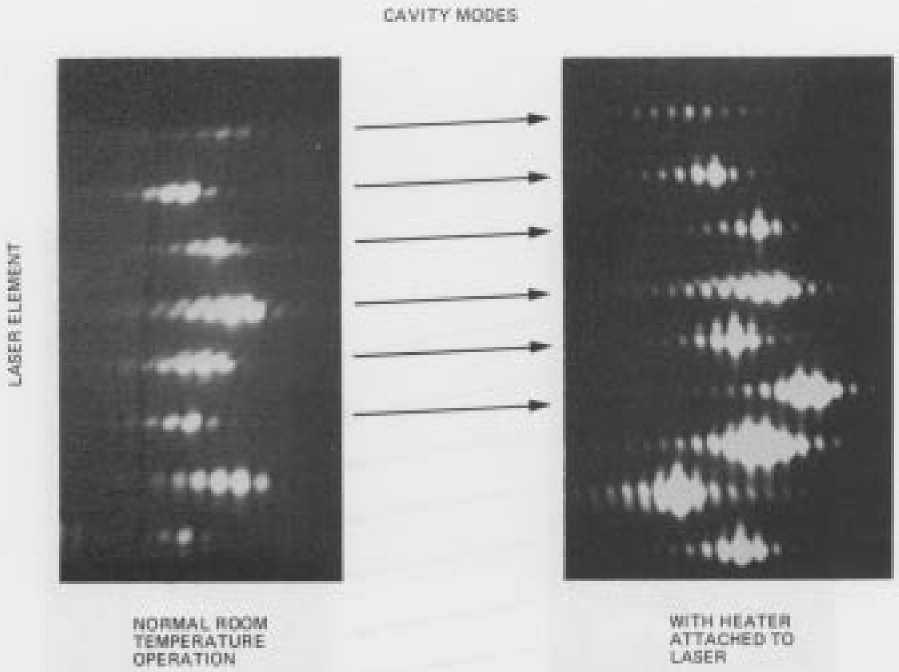

Fig. 5. Spectral profile of the slave array before and after heating

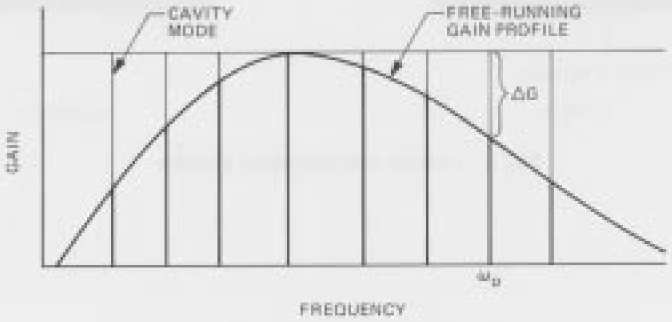

Fig. 6. Condition for injection locking

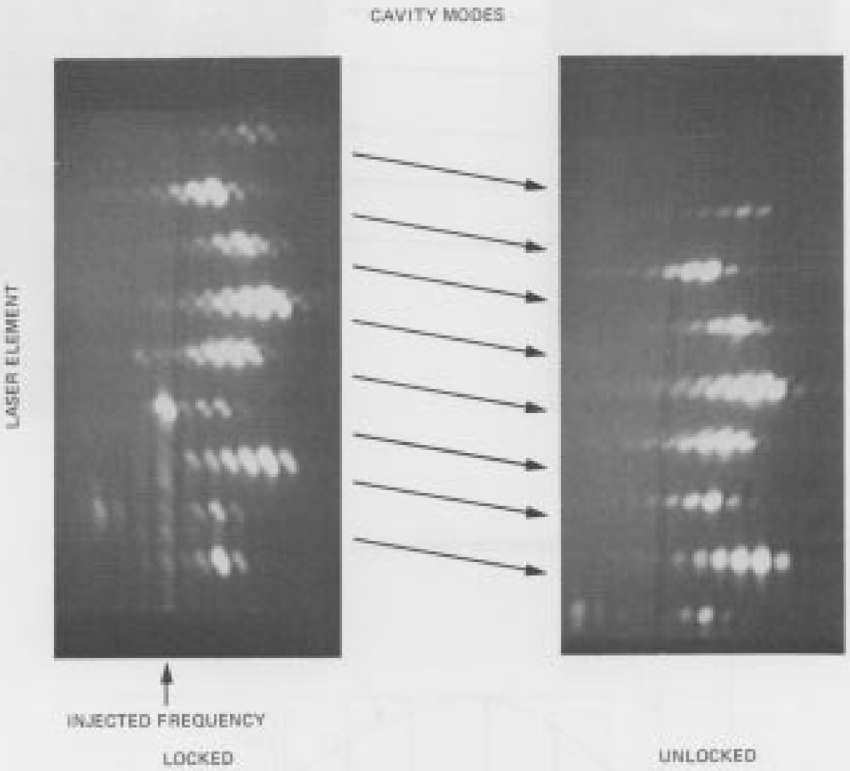

Fig. 7. Locked and unlocked spectra