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A SURVEY OF BEAM-COMBINING TECHNOLOGIES FOR LASER SPACE POWER TRANSMISSION

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Summary

Laser beams of high optical quality and high average power (~ 1 MW) are essential for effective and practical power transmission in space. Such laser beams could be obtained by combining multiple laser arrays.

In this survey, a review of various beam-combining methods is made to identify the most promising techniques. Simultaneous coherent amplification and injection-locking of a large number of laser diode arrays with a master laser diode to obtain one coherent beam are suggested as suitable beam-combining technologies for space power transmission.

I. Introduction

Recent advances in the development of high power (> 1 W) laser diodes have revealed new horizons in their applications [1, 2]. A recent study [3] of four electrically pumped laser systems (KrF, copper vapor, laser diode array, and carbon dioxide), all scaled to 1 MW laser output for space power transmission, shows the laser diode array to be the most efficient. However, phase matching and beam quality for long-distance transmission are technological obstacles.

In this study, the basic concepts of several beam-combining techniques and their application to laser diode arrays for obtaining phase matching and suitable beam profiles are presented.

Basically, beam-combining methods can be divided into two groups: incoherent and coherent methods. Although the incoherent method is straightforward to implement, it has the disadvantages of a large beam divergence and a limitation on up-scaling as will be discussed. The coherent method is promising in principle because it can produce laser beams of high power and small divergence that are necessary for long distance (> 1,000 km) power transmission.

A few examples of incoherent and coherent beam-combining methods are reviewed in Part II, and recommendations are made in Part III. In Part IV, discussions of these methods with respect to long distance power transmission in space are presented and a "proof-of-principle" experiment for the recommended beam-combining method is proposed. The conclusions are presented in Part V.

II. Review of Typical Beam-Combining Methods

A number of beam-combining methods for laser diodes have been reported [4 - 7]. However, these were developed for space data communication and are not directly applicable to space power transmission. Some of those methods are reviewed here. Attempts are made to recognize the merits of each of the methods in reference to space power transmission.

<u>Incoherent Beam-Combining Methods</u>

A. Wavelength multiplexing.

Figure 1 shows a beam-combining system that uses the wavelength multiplexing technique [4]. This is possible because of the broad bandwidth of laser diode gain. By using a number of color bandpass filters with different spectral transmittances (see Figure 1(b)) and laser diodes emitting at corresponding wavelengths, about fifty beams can be combined (assuming a spectral distribution of 750-850 nm for the GaAs laser diodes and taking the spacing between peak transmittances of the bandpass filters as about 2 nm). In Figure 1(a), the n-th bandpass filter transmits only the n-th laser beam and reflects other beams, so all beams are combined after the final bandpass filter.

The system is simple and straightforward and does not have any serious technical problems. This may be used to combine incoherently the final amplifier outputs coming out from several coherent amplifiers with different wavelengths will be discussed in a following section. This kind of hybrid system may make it easier to get 1 MW than from the single-wavelength system (also discussed later) because the technology needed to construct one series of amplifiers of about 20 kW can be used to construct the whole system.

B. Diffractive spreading.

Figure 2 depicts a system which takes advantage of diffractive spreading in the far field [8]. In reference 8, 18 individual beams are sent through different areas of the same telescope mirror in the same direction. In a far field of several thousand kilometers, each beam is spread over a few hundred meters, and all the beams add there incoherently. This system is also straightforward and good for space data communication, but the number of laser diodes to be combined is limited by the size of the telescope mirror, and the divergence is determined by the spot size d of each beam on the telescope mirror, not by the size of the telescope mirror D. (See sketch in Fig. 2.) The principle of the technique, however, can be used in transmitting beams from one amplification stage to the next in a traveling wave amplifier (TWA) or injection-locked system.

Coherent Beam-Combining Methods

A. Common external cavity.

Figure 3 is a schematic for beam-combination that uses a common external cavity. The spatial filter forces the beams from individual laser diodes to couple with each other and thus to lase in phase [9]. This system coherently combines beams, but the complexity of the system and the limitation in the number of laser diodes because of the finite size of the optical components make it inadequate for our goal.

B. Binary grating.

Figure 4 is a schematic of beam-combining using binary grating. Unlike the ordinary continuous sine or sawtooth shape grating, it is designed to give discrete on-off type phase delay to produce diffracted beams of equal intensities. Figure 5 shows the typical groove shape of the binary grating for seven equal diffraction orders. For beam-combining, it is used in reverse, and the beams to be combined should have constant phase relationships $\varnothing_1, \varnothing_2, \ldots \varnothing_N$ among them. This may be done by injection-locking from a master laser.

It has been proven experimentally that the phase binary grating can combine many beams in two dimensions (10 x 10) with relatively high coupling efficiency (> 70%) [10-12].

Binary gratings can be made on glass plates by lithographic techniques. Their efficiency, robustness, and simplicity make them suitable for high power beam combination. Because of the finite angular separation between adjacent lasers, the number of lasers to be combined by a binary grating will be about 10 in one direction.

However, it can still be used to combine beams coming from several different amplifiers at the final stage, as will be explained in the next section.

C. Phase conjugation.

Inherent coupling of incident waves in phase conjugators by degenerate four-wave mixing also provides a means for beam combination. Coherent coupling of a few laser diodes or dye lasers was demonstrated experimentally with a $BaTiO_3$ crystal as the nonlinear medium [13-14]. Figure 6 is a schematic diagram of the experimental system using laser diodes and the $BaTiO_3$ crystal. When beams irradiate the same crystal, the beams are coupled to each other by the photorefractive index gratings. It is not clear yet if this method is suitable for our goal because of the complexity of the system and the limitation on the number of laser diodes to be coupled. The number of laser diodes is ultimately determined by the damage threshold and the geometrically acceptable angle Q_M (see Fig. 6) of the crystal.

III. Beam-Combining by Simultaneous Amplification and Injection-Locking

A. Simultaneous amplification

Figure 7 shows the basic concept of obtaining coherent output by simultaneous amplification through a laser diode array. The beam from the master laser diode is fed into every amplifier diode element to be amplified simultaneously. Previous publications show that a traveling-wave amplifier can produce beams of high quality (diffraction-limited) and high power [15-18]. It is simple in structure and has possibilities for up-scaling if multiple-stage amplifier arrays are used.

It is essential to study the coherence of outputs from different amplifier diode elements and to measure the reduction of coherence when the beam passes through several amplification stages. This kind of study will reveal the ultimate limit on the up-scaling of beam-combining technology using laser diodes.

To suppress lasing in the amplifying laser diode and also to enhance the saturation intensity and output power, the facet reflectivity should be less than about 0.3% (anti-reflection coated). Coupling into the laser diodes is done by a microlens array L1 and L2. Cylindrical lenses can be used also for laser diode arrays in which the separation between diode elements is a few tens of microns.

Figure 8 is a schematic of a multistage amplifier system consisting of about a million laser diodes which can produce a 1-MW output from the final stage. Each amplifier line is an array of three to five amplifiers in series for 10 kW. It is designed that each stage shall amplify input 100 times. The output phase of each amplification stage is electro-optically controlled, and the output beams are combined by a binary grating to produce one coherent beam. The beam quality and power of the master oscillator should be good and highly reliable.

If the signal gain in each stage is G and there are n stages, then to get 1-MW ouput

$$G^n = 10^6 \text{ W}$$

$$n = 6/\log_{10} G. \tag{1}$$

Only three stages are necessary for a gain of 100, and four stages for a gain of 30. The latest gain reported is 81 (3.9 mW to 315 mW [19]), so four stages will suffice for a 1-MW output, even if losses during beam distribution are taken into account.

Figure 9 shows a hybrid system which takes advantage of the coherent amplification and the wavelength multiplexing of Figure 1. Since the output wavelength of GaAs laser diodes varies between 750 nm and 850 nm, there may be 50 coherent amplification lines with a wavelength difference of 2 nm between adjacent lines. Each line generates 20-kW coherent output, and the outputs are combined incoherently by the laser mirrors of almost 100% reflection at the corresponding wavelength and almost 100% transmission at other wavelengths. The difficulty of phase matching is greatly reduced from that found in the single-wavelength system of Figure 8, and still the beam quality of the final combined output will remain almost the same. Also, many master laser diodes greatly reduce the probability of system breakdown.

Figure 10(b) shows a cross section of the detailed structure of a proposed laser diode array amplifier. Recently a laser diode array bar of 1-cm width with 200 diode elements inside demonstrated a maximum output power of 38 W [20]. By putting such array bars together or by making a laser diode array bar with broad-area laser diodes (the gain element is about 50 μm-100 μm wide) inside as in Figure 10(a), we can think of the laser diode amplifier module as the basic building block of the whole system.

The coupling of the input beam into the module can be done using a cylindrical lens. The output from the broad-area laser diode array will become almost a plane wave by diffractive superposition.

Heat is removed by a thermoelectric cooler and a heat-removing channel.

B. Injection-locking

Injection-locking of laser diodes can also produce a coherently combined output [21-23]. When a beam from a master laser is injected into a slave laser, the phase and wavelength of the slave laser are locked to the incident beam because the matched slave mode has higher gain and other modes are suppressed. The fundamental characteristics of the injection-locked beam are almost the same as the traveling-wave amplification (TWA). Figure 11 shows the concept of obtaining coherent output from an array of injection-locked laser diodes. It can be easily extended to a large two-dimensional array. Previous experiments show that the locking bandwidth is about 10 GHz, which is about the fall width at half maximum (FWHM) of the mode. This requires a temperature stability of about $\pm$ 0.1°C.

Phase stability between laser diode amplifiers is a critically important factor in achieving a stable beam-combination. Kobayashi and Kimura showed experimentally that the phase of the locked output is very stable with time [24]. The following analysis shows the relationship between phase and driving current stability.

It is known that the refractive index of a laser diode gain medium changes almost linearly with injected carrier density [25-26]. When the current is increased from zero to threshold, the index change reaches about 0.02.

The optical path length change is given by

$$\Delta (nL) = (\Delta n) L + n \Delta L. \qquad (2)$$

The thermal expansion ΔL of the cavity length is negligible, but the index change Δn can contribute significantly to phase change. In order to have the optical path change less than about 1/20 wave for L = 300 μm, the change of refractive index should be less than 1.4×10^{-4}. This means the driving current variation should be less than 0.5% of the operating current.

IV. Discussion

There are two viable techniques for coherent beam-combination to produce a 1-MW laser diode system. One is injection-locking of a large array of laser diodes with a master laser diode of good quality, and the other is simultaneous amplification (TWA) through a large array of laser diodes from a master laser diode. Injection-locking is a very promising technique for coherent beam combination of many laser diodes. Goldberg and Weller [19] injected 3.9 mW from a master laser diode into a 20-element array and obtained 315 mW of almost diffraction-limited output in a single longitudinal mode.

The TWA is also very promising. It can generate a high quality, powerful beam. It is believed that the above two methods are almost equivalent in terms of beam quality. From a practical point of view, however, the TWA looks better because it can generate higher power with a much larger gain-bandwidth than the injection-locked system [27]. Typical gain-bandwidths of the injection-locked and TWA systems are of the order of MHz and THz, respectively. The large gain-bandwidth of the TWA means that fluctuations in temperature and/or driving current in the amplifying laser diode do not significantly affect the characteristics of the whole system. Usually there exists a large temperature dependence of wavelength change (0.25 μm/° C) in laser diodes. The temperature stability needed for the injection-locked system to maintain lock within 10 GHz is about 0.1°C. The TWA does not have such a temperature sensitivity, and this makes it desirable as the basic amplifying element in laser-diode beam combination systems.

By passing the beam from the master laser diode through several amplification stages, it is possible to obtain one powerful, coherent beam. Three or four amplification stages will be enough to get 1-MW output from a million 1-W laser diodes consisting of the final amplification stage for the gain of 100 or 30, respectively.

The main points to be studied in the development of a laser diode array amplifier by using injection-locking or a TWA are coherence of the amplified beam, beam profile control, phase control, and noise. A small-scale beam-combining experiment will be desirable for the proof-of-principle.

Figure 12 depicts an experimental system for measuring the coherence between two amplified or injection-locked laser diodes. The two beams coming from the slave lasers interfere with each other, and the interference fringes are monitored and analyzed by a video camera and computer system.

Figure 13 illustrates another proposed experimental system for measuring the reduction of coherence when the beam passes through several amplification or injection-locked stages. The final amplified or injection-locked output beam and the original beam interfere at the screen and are analyzed there.

V. Conclusions

The review reveals that a traveling-wave amplification (TWA) is the most promising method for generating the high average power (> 1 MW) necessary for space power transmission. In order to assess the feasibility of up-scaling, it is essential to study the coherence of amplified beams and measure the reduction of coherence caused by successive amplification stages. Initially, work in the following areas will be important:

- Coherence of amplified beams.
- Stage coupling technology.
- Beam profile control and measurement.
- Phase stability.

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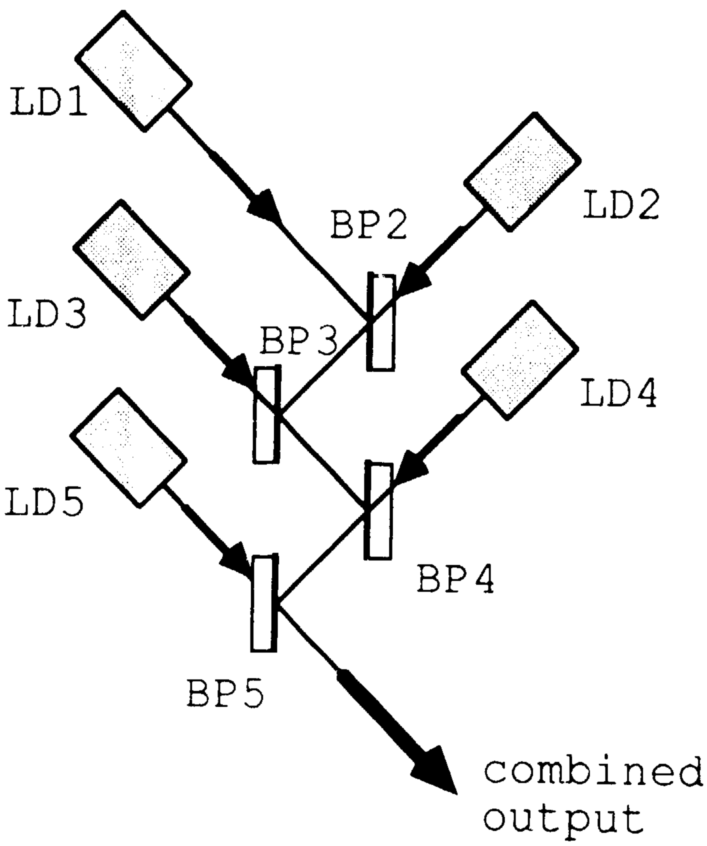


(a) wavelength multiplexing system

Fig. 1. Wavelength multiplexing. (a) multiplexer beam-combination system, LD_n; laser diode with wavelength ln, BPn; bandpass filters with maximum transmission at the wavelength ln.

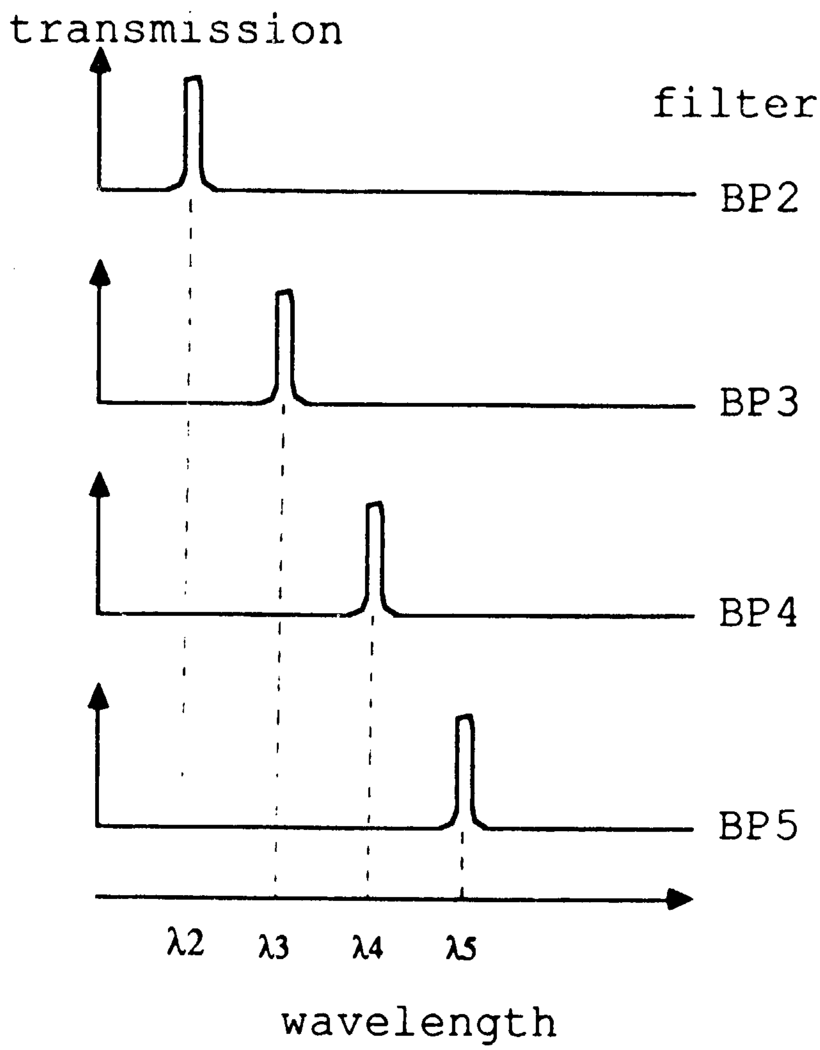


Fig. 1. Wavelength multiplexing. (b) filter transmission.

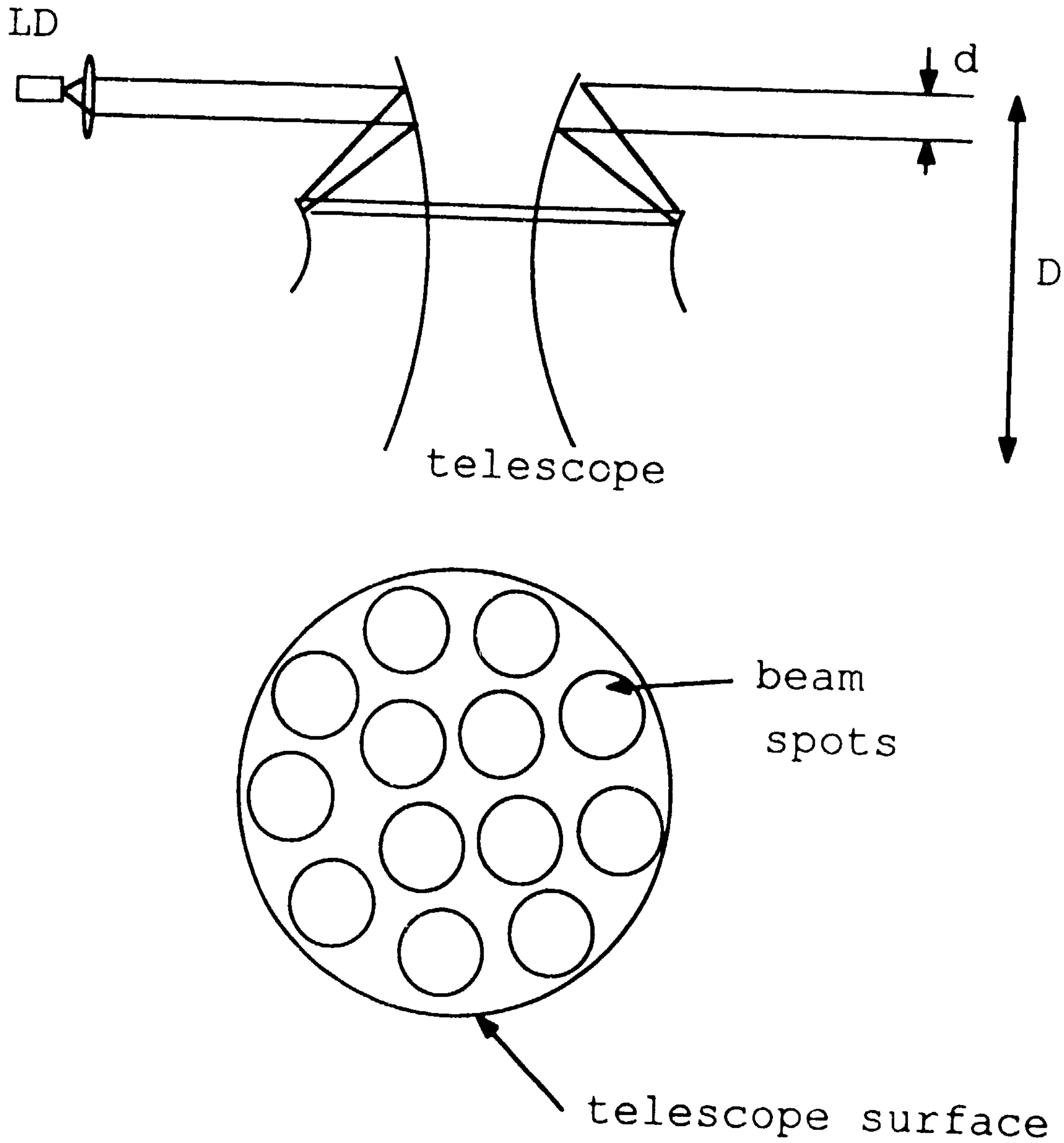


Fig. 2. Diffractive beam-combination system, d; individual beam diameter, D; telescope diameter.

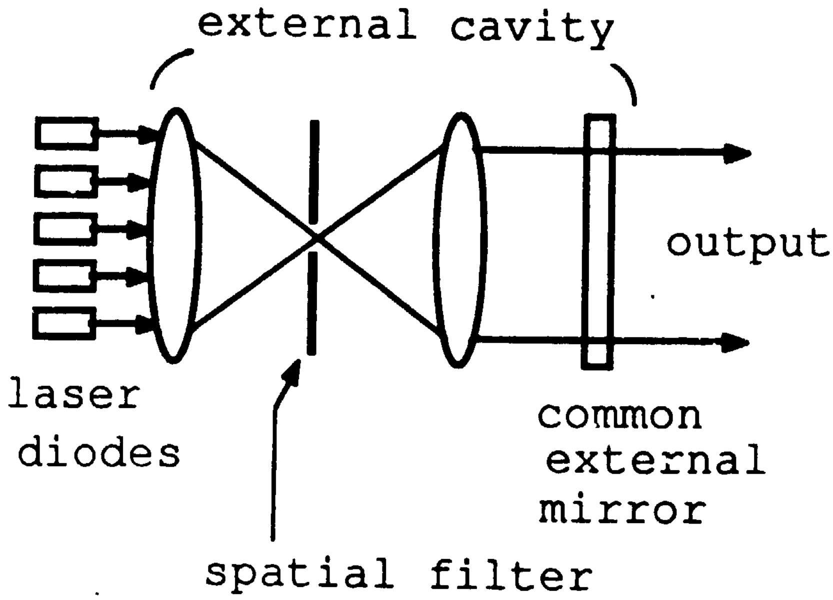


Fig. 3. Common cavity beam-combination system.

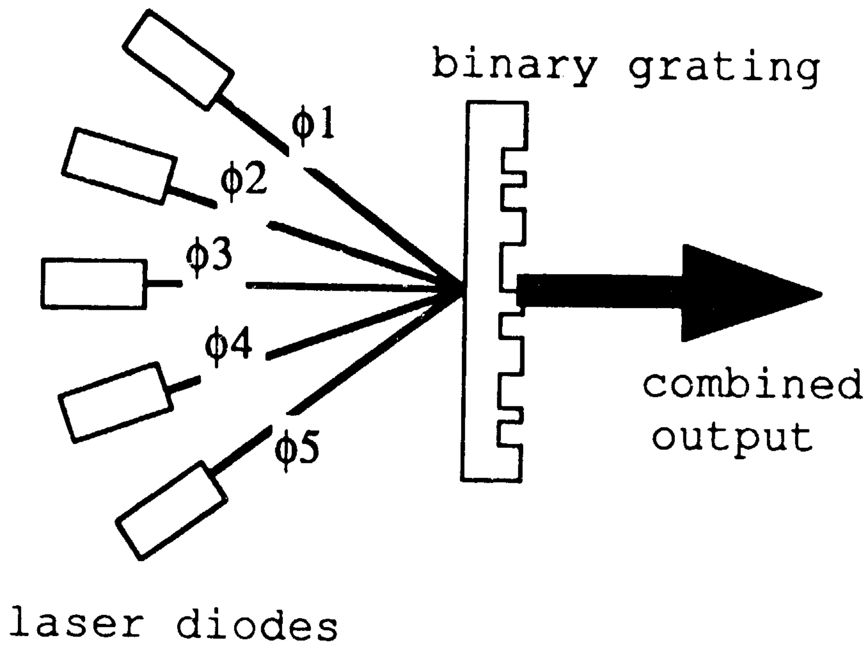


Fig. 4. The schematic system of beam-combining using binary grating $\phi_1, \phi_2, \ldots \phi_N$ means that the beams should have constant phase relationship with each other.

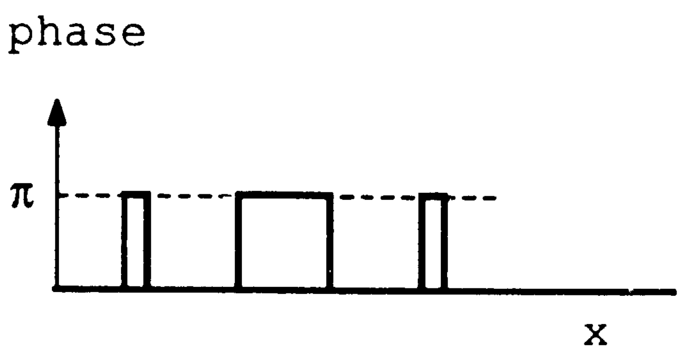


Fig. 5. Binary grating beam-combination system. (a) typical binary groove shape.

(b) intensity distribution of diffraction orders

Fig. 5. Binary grating beam-combination system. (b) binary grating intensity distribution.

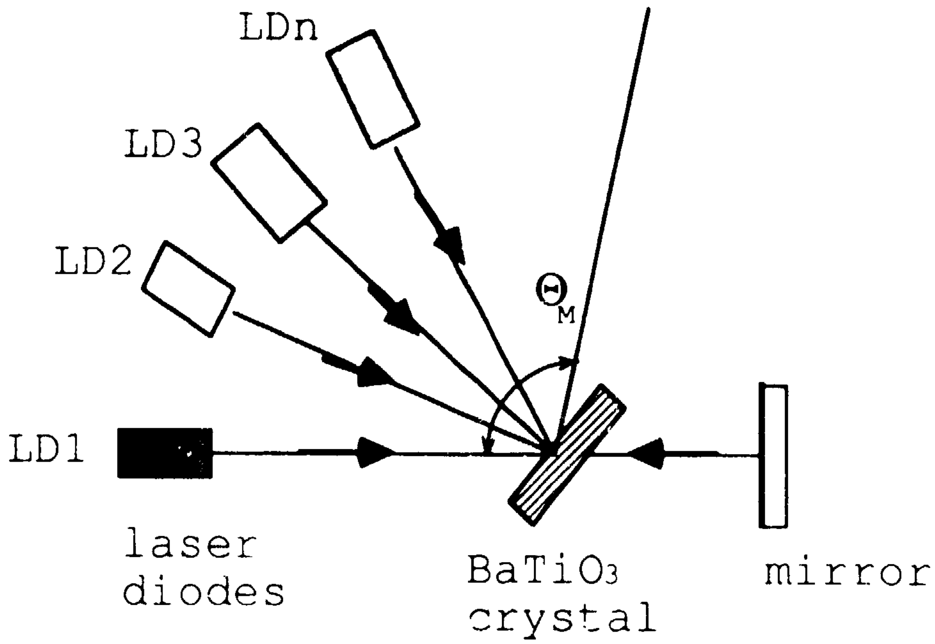
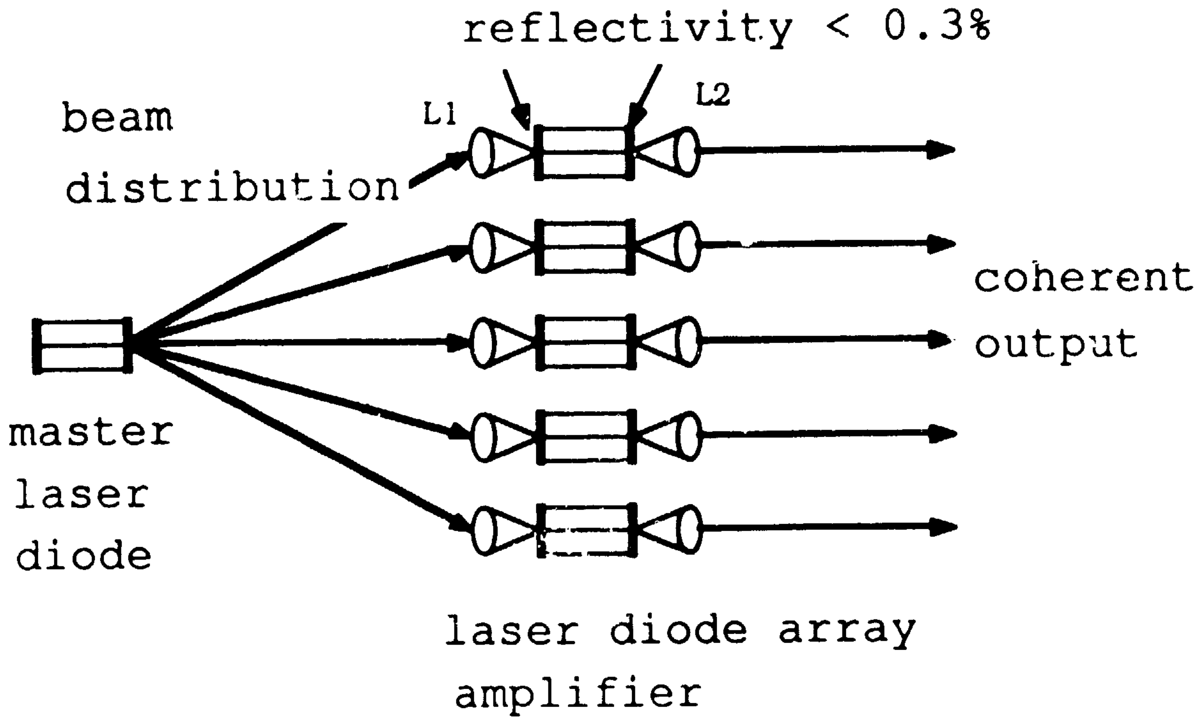


Fig. 6. Phase conjugation beam-combination system. LDn; nth laser diode.



L1, L2 Input and Output Microlens Arrays

Fig. 7. Amplification through laser diode array.

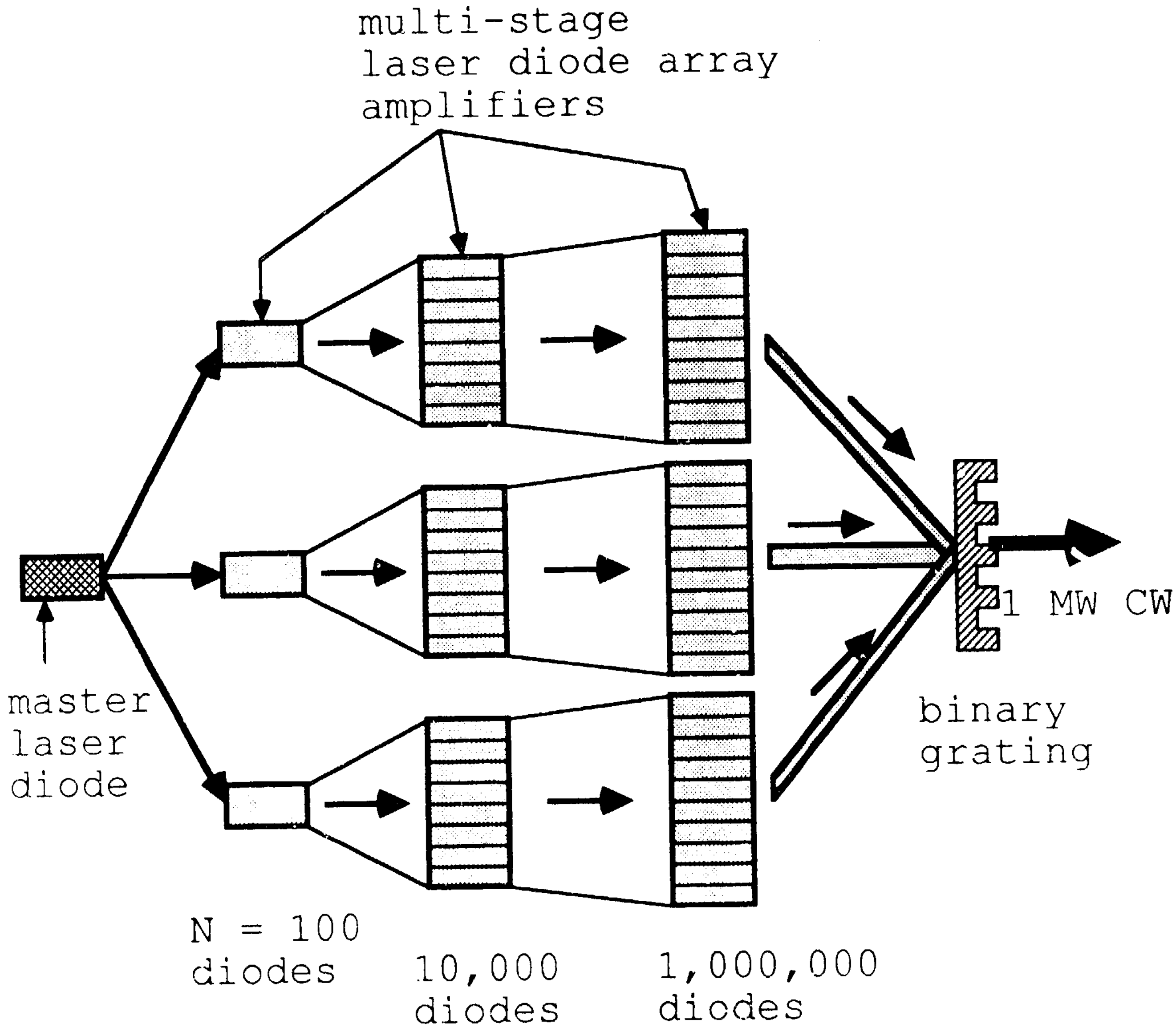


Fig. 8. Multi-stage beam-combining and amplification.

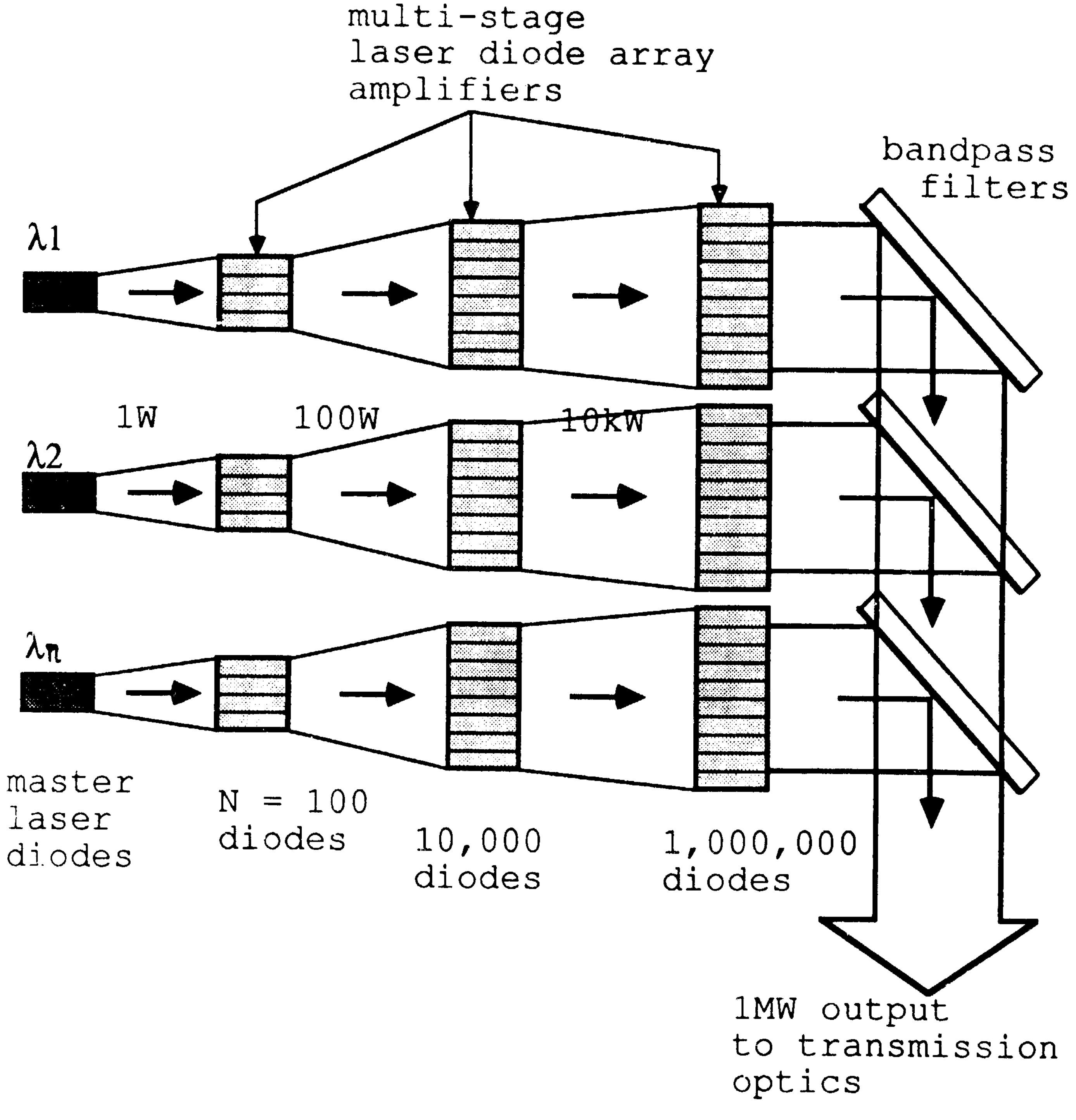


Fig. 9. Hybrid multi-stage beam-combination system.

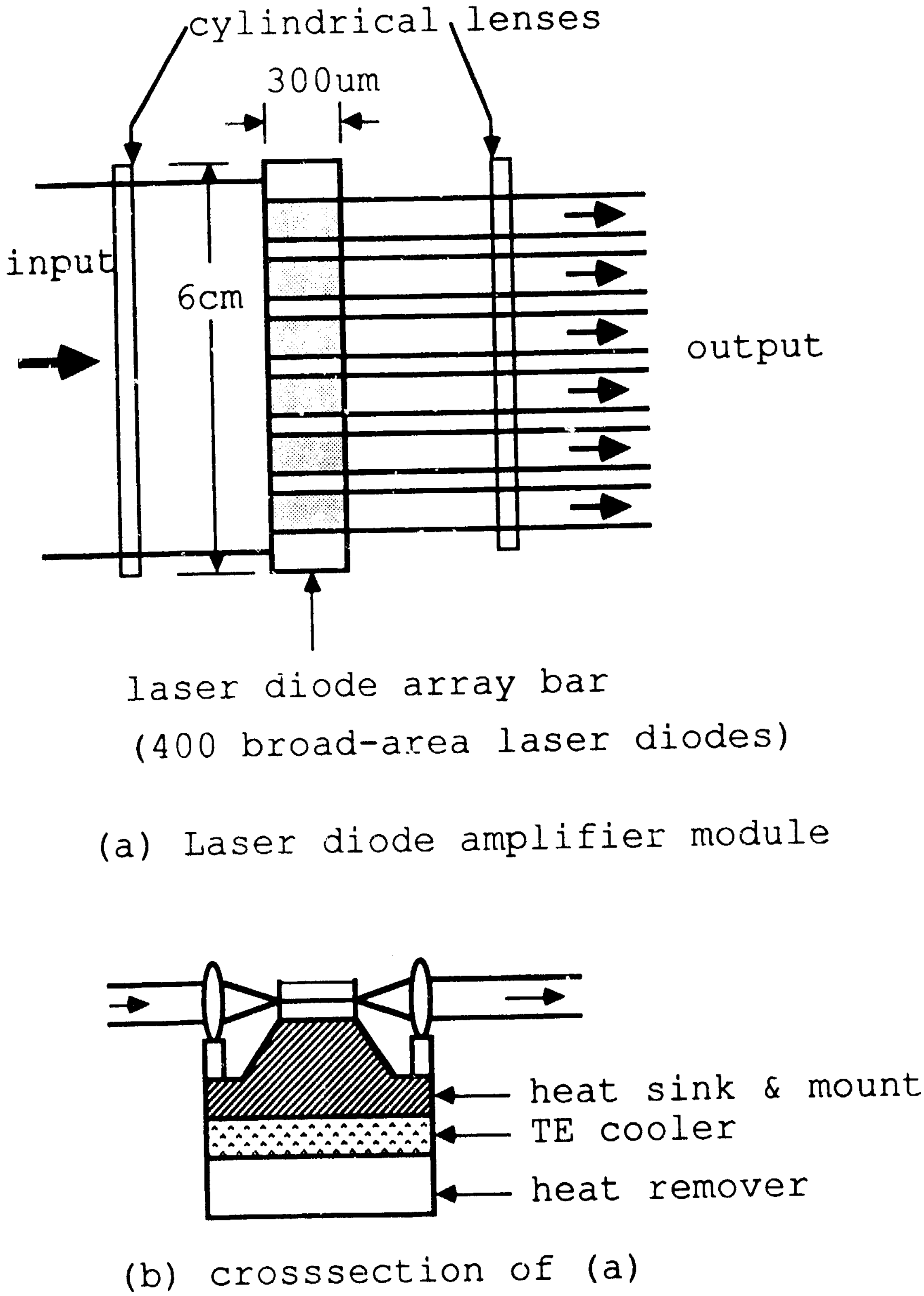


Fig. 10. Broad-area diode array structure.

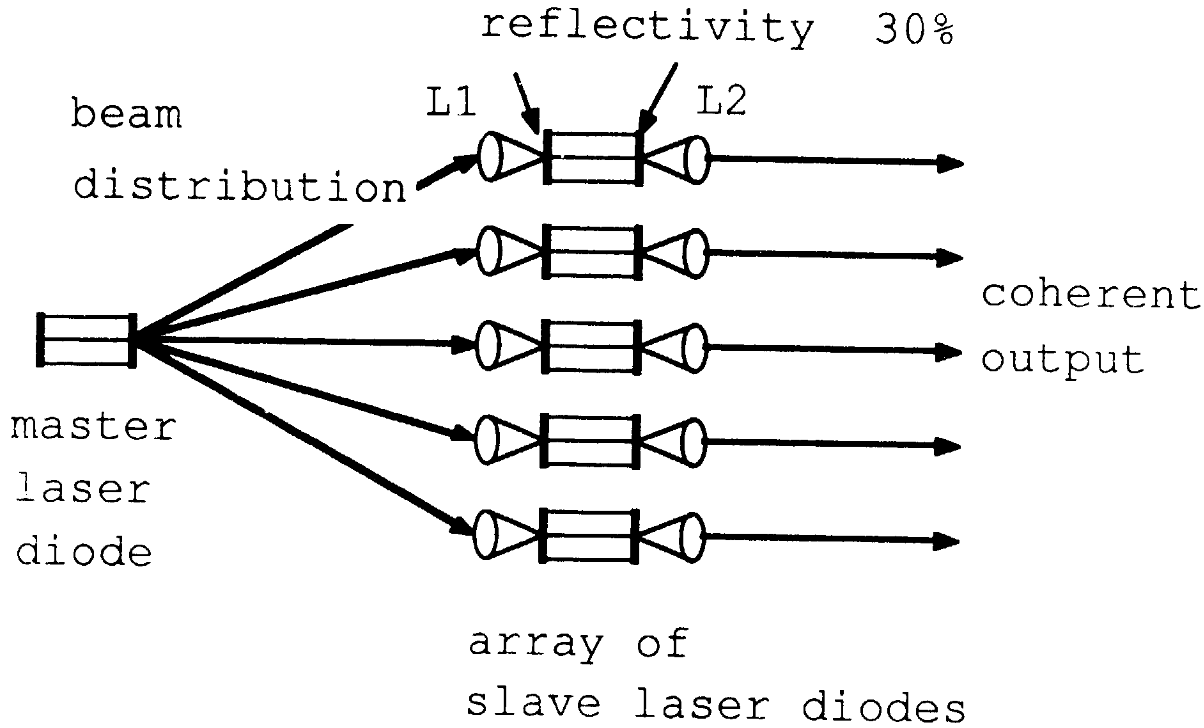


Fig. 11. Injection-locking of laser diodes.

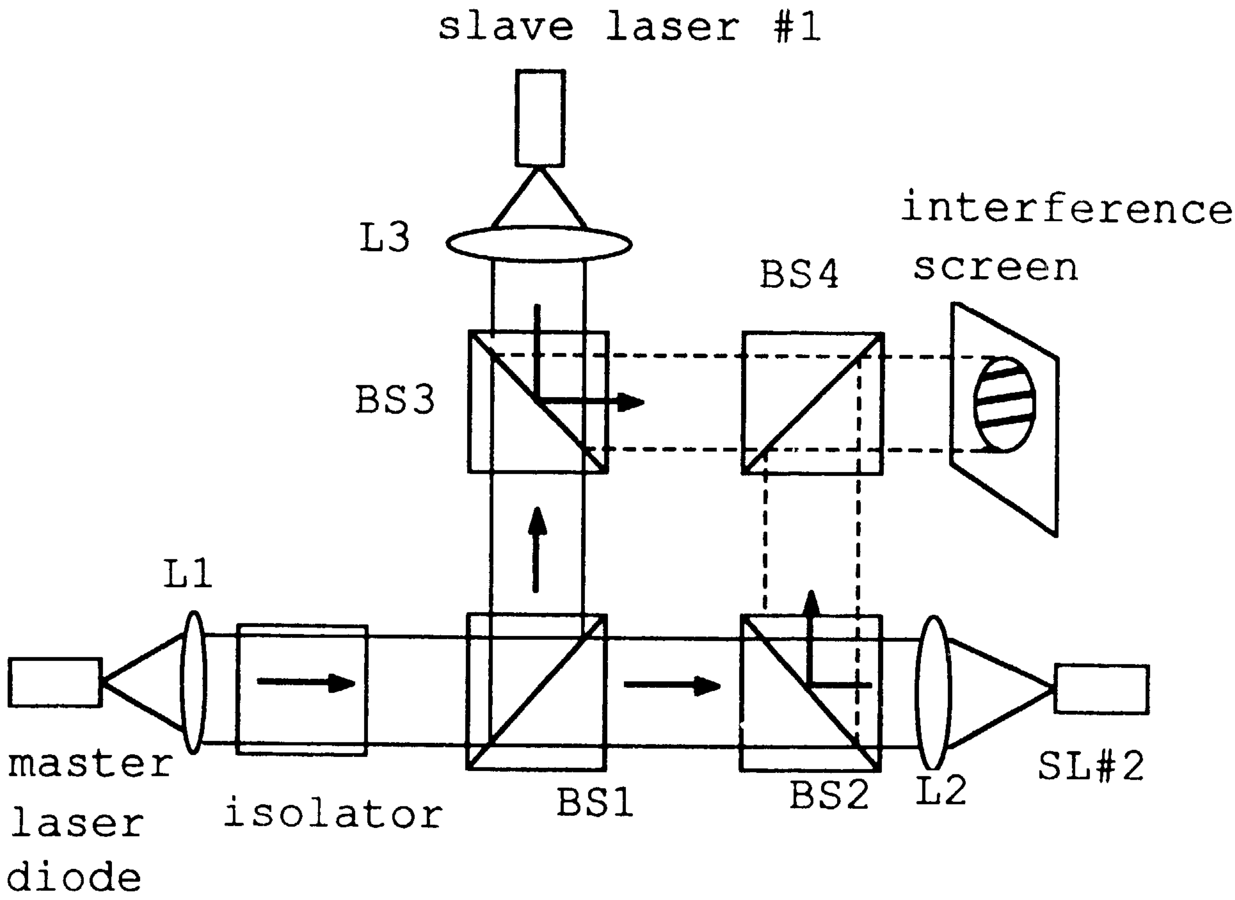


Fig. 12. Coherence measurement experiment. L; coupling lenses, BS; beam splitters.

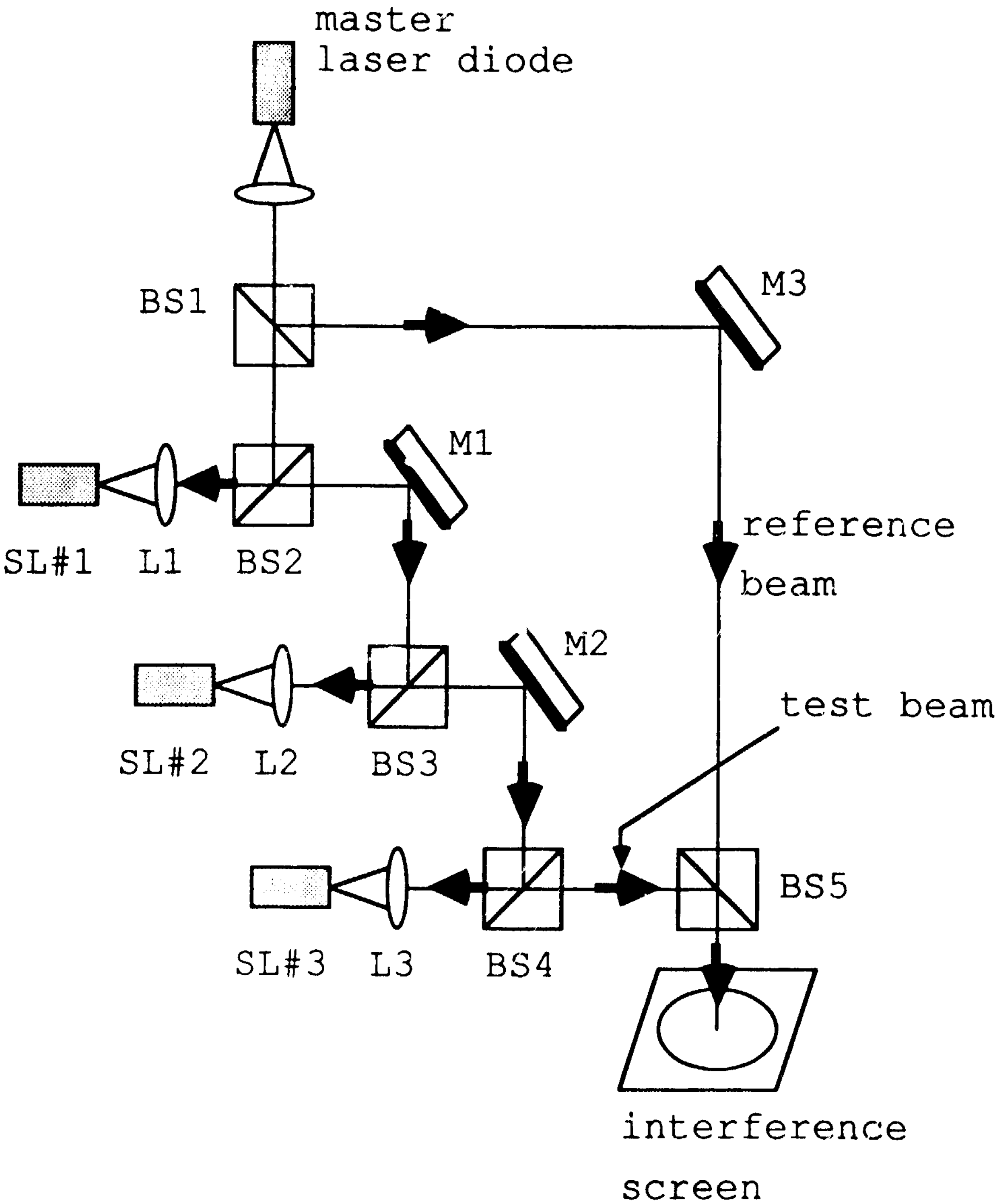


Fig. 13. Coherence reduction measurement system. A proposed experimental system for measurement of reduction in coherence through multi-amplification stages. SL; slave lasers, L; coupling lenses, BS; beam splitters, M; mirrors.

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16. Abstract

The combination of laser beams holds much promise for obtaining powerful beams. This report surveys methods for beam combination (coherent and incoherent) and identifies two of them as the most effective means for achieving high power transmission in space. The two methods as applied to laser diode arrays are analyzed, and potentially productive work areas for the advancement of technology are delineated.

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