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The transmission of large amounts of power in space by laser beam (diode lasers, in particular) requires an array of lasers to increase total power. Concentration of the beam requires some degree of coherence. Temporal coherence can be obtained by locking amplifiers to a master oscillator. However, spatial coherence is not so easily created or maintained. Many mechanical, thermal, and electrical factors oppose it continually. A very simple method is described for creating and maintaining a degree of spatial coherence by simply turning selected diodes ON or OFF. The degree of coherence can be chosen; the greater the coherence, the larger is the number of lasers required for a given power and the longer the lifetime of the array. An experiment for analyzing performance, verifying theory, and evaluating critical parameters is also proposed.

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Summary

A technology for transmitting high power by laser beam over large distances using a quasi-coherent array of lasers is described. This technology achieves quasi-coherency by turning OFF selected laser elements, rather than trying to correct their phase as present technologies do. Such an array puts less power into a specified area in the far field than a fully coherent array but gains two major advantages: (1) laser array elements are greatly simplified and less expensive and (2) array lifetime can be lengthened. The degree of coherency can be chosen. The greater the coherency, the greater is the lifetime of the array (for a specified power transmission requirement). More laser elements remain inactive. Also, by making array element selection a dynamic process, the technology can actively correct any phase changes induced in the array. The technology is analyzed, results of a computer experiment are presented, and a laboratory experiment for further development of the technology is proposed.

Introduction

For many years, NASA has studied the transmission of power by laser beam (refs. 1 and 2), with potential applications identified both in space and on Earth. Such applications require high power (up to megawatts) diffraction limited laser systems. One method to obtain such systems is to assemble arrays of less powerful lasers which can be scaled to the laser power required. Arrays also lend themselves to building the large apertures required for transmission over large distances. The larger the transmission aperture is, the smaller the received laser spot size for a given range. Arrays have usually been described in terms of their *ultimate* power transmission capability (i.e., the maximum power that a *coherent* array could transmit into a specified area in the far field). Coherent arrays transmit optical amplitudes that are in phase in space and time. Although coherent arrays are feasible, they are very difficult to obtain in practice. They require complex and expensive electro-optical components that are still challenged by the dynamics of a real system (i.e., heat distribution, alignment, mechanical stress). Thus, the questions arise: "Is the power transmission loss due to incomplete coherence worth the cost of obtaining complete coherence?" and "Are there other advantages of a partially coherent array?" These questions have led to an idea labeled "dynamic selection of emitting laser array elements." This idea represents a new approach to obtaining concentrated laser power in the far field. In this approach, laser array elements are not "forced" to be perfect (coherent) but are simply turned OFF if they are sufficiently imperfect (incoherent). The advantages of this approach are discussed, some of the results of a computer experiment with this theory are presented, a practical laboratory experiment is proposed, and its purposes are enumerated.

Dynamic Selection of Emitting Laser Array Elements

The dynamic selection of emitting laser array elements (ref. 3) is, essentially, a simple method for obtaining a concentrated far-field radiation pattern from an array of lasers that are already temporally coherent but have random phase errors due to optical path differences or effects that can be interpreted as such. The idea represents a compromise between the beam concentration obtained with fully coherent laser arrays and that obtained with incoherent laser arrays. The price paid in reduced array coherence buys an easily implemented, partially coherent array with greatly simplified laser elements and extended lifetime. (See ref. 4 for an overview of related technology in the PILOT program and descriptions of complex laser systems that attempt full correction of incoherence.) The degree of coherence is adjustable. If a large degree of coherence is chosen, not many array elements will be turned ON because only a small fraction will meet the optical path-length-difference requirements. The resultant output power can be increased by increasing the total number of laser array elements. Since a large degree of coherence activates a small fraction of array elements, the other elements can be activated at later times to provide extended lifetimes.

Elements of the array need only be aligned (emitted beams approximately parallel) and temporally coherent (same frequency). The phases of the elements (spatial coherence) are randomly distributed. Partial coherence is obtained by simply turning OFF those elements that are not within a specified phase error of a reference element (and turning ON those that are). (Semiconductor waveguide amplifiers or similar devices for EXACT phase control are not needed.) This is a dynamic process; that is, each element is reexamined at later times to determine whether they should remain OFF or ON. In this manner, the array is continually readjusted to compensate for any factors that tend to destroy spatial coherence.

If, for example, only those laser elements that are within $\pm 90^\circ$ of the reference element are turned ON, about one half of the total laser elements would be turned ON (assuming, for simplicity, that the maximum phase variation is a multiple of 2π radians). The total number of laser elements would have to be adjusted so that the half that are turned ON would emit the required power. The other half of the laser elements are also within $\pm 90°$ of a (unspecified) reference element. At some later time, therefore, they can be turned ON (and the first group turned OFF) to extend the useful life of the array. The status of a laser element (ON or OFF) is determined by comparing the combined intensity of the element and the reference element with that of the reference element alone. If the combined intensity divided by the intensity of the reference element alone exceeds a specified ratio, the element is "tagged" to be turned ON; otherwise, it is tagged to be turned OFF. After every element of the array is scanned individually, those tagged to be ON are turned ON. This "start-up" scan process is repeated at later times until the diodes chosen for activation remain unchanged. When this quasi-equilibrium is established, a more efficient "steady state" scan mode can be adopted. The steady state mode would leave laser elements ON (or OFF, as determined by start-up) during a scan, but would reverse the state of each element sequentially and, from the effect on far-field intensity, determine whether that state should be maintained or reversed.

Computer Experiment

The basic theory of the dynamic selection idea has been implemented in a computer program. The program simulates a 7×15 rectangular array of square diode laser elements in a 32×32 field and computes the resulting far-field patterns by using fast Fourier transforms. The elements of the array that are turned ON and their phases are determined by a computer algorithm. In figure 1(a), all array elements are ON and in phase. This is the classic fully coherent array and its classic far-field pattern is shown in figure 1(b). (See ref. 5.) In figure 2(a), the array elements have been given a random phase distribution within the limits 0 to 2π radians and only those elements within $\pm\pi/2$ radians of an arbitrarily chosen reference element have been turned ON. Figure 2(b) is the resulting far-field pattern. It shows a large central lobe surrounded by laser speckle and demonstrates the theoretical viability of the basic concept. Reference 3 shows that a similar far-field pattern is generated when the ON/OFF status of the array elements of figure 2(a) is reversed. (This means that array lifetime can be doubled.) Reference 3 also shows that the far-field beam can be "steered" by moving the far-field sensor. The computer program does not vary the phases of the elements with time. Therefore, the dynamic aspects of the scanning process have not been simulated.

Scanning Options

The intensity ratio specified previously is given by (ref. 6)

$$\frac{I}{I'} = 2(1 + |\gamma_{12}| \cos\ \Phi) \tag{1}$$

where

I intensity of reference laser element and selected laser element combined

I' intensity of reference laser element alone

γ_{12} complex degree of coherence, $\dfrac{I_m - I_m}{I_m + I_m} \approx 1.0$

Φ phase angle between emissions of two lasers

(Laser elements are assumed to be diffraction limited and uniformly intense.) Thus, specifying I/I' is equivalent to specifying an approximate phase angle between two lasers emissions.

If a large number of lasers are turned ON and their phase deviations are uniformly distributed between $-\beta$ and $+\beta$, the sum of their amplitude is given very accurately by

$$A = \frac{N}{2\beta}\int_{-\beta}^{\beta} \cos\ \Phi\ d\Phi = \frac{N}{\beta}\int_{0}^{\beta} \cos\ \Phi\ d\Phi \tag{2}$$

$$= \frac{N\ \sin\ \beta}{\beta} \tag{3}$$

where

N total number of diodes ON

β maximum phase deviation from reference laser element

Φ incremental phase angle

(The amplitudes of elements have been added. Each element with a $+\Phi$ phase deviation has a matching element (conjugate) with a $-\Phi$ deviation. The imaginary components of matching elements cancel; only the real components ($\cos\ \Phi$) are left to be summed.)

The corresponding intensity A^2 expressed as a fraction of the fully coherent intensity N^2 is graphed in figure 3. The most incoherent group of diodes that constructively interfere are those that have phase deviations within $\pm\pi/2$ radians (90°) of the reference diode. They produce 40.53 percent of the fully coherent intensity. With an improvement on phase deviations, say to $\pm\pi/4$ radians (45°), the intensity becomes 81 percent of the fully coherent intensity.

In general, however, phase deviations are not uniformly distributed within some maximum values. Neither is their maximum value an exact multiple of 2π radians. Although a large number of diodes guarantee some uniformity in distribution, it is almost certain that the total range of deviations of ALL DIODES (ON and OFF) will not be an exact multiple of 2π radians. Either there will be some overlap past 2π radians in a phase diagram or some unfilled gap. If a reference diode is chosen such that the range of phase deviations about it lies entirely outside or inside the gap or the overlap, a very good uniformity can be obtained. Otherwise, the distribution will be nonuniform. A nonuniform distribution (or a distribution inside an overlap) can be beneficial, however. Suppose, for example, ALL diodes deviate within 2.5π radians (as shown in fig. 4), and the reference diode is at $\pi/4$ radians in the phase diagram (right in the middle of the overlap). For $\pm\pi/4$ radians about the reference diode, there will be twice the number of phasors per radian as there are outside this region. However, the number of phasors per radian for the whole 2.5π radians will have decreased by a factor of 1.25 ($N/2\pi$ to $2N/5\pi$). Therefore, the amplitude will be 1.6 (2.0/1.25) times greater than that of a nonoverlapped distribution, and the intensity will be 2.56 times greater.

To take advantage of distribution nonuniformities, the scanning strategy described needs modification. The modification involves RECORDING the intensities of the individual diode lasers (not just tagging them) so that overlaps and gaps in the phase distribution can be determined and used.

The Ideal System

The ideal system uses hundreds of laser diodes in a compact array. Individual diodes are cooled by thermoelectric coolers (TEC's) backed by flowing liquid coolant. The TEC's provide the precise temperature control required by some of the scanning options. All the lasers are locked in frequency to one master laser oscillator and are powered by transient-free, switchable power-supply units. The power units are controlled by digital switching circuitry from a digital telemetry unit. The telemetry unit would receive intensity-modulated signals from the remote sensing unit, which is a photomultiplier tube coupled to the receiving aperture by a movable light pipe. Intensity signals detected by the photomultiplier are transmitted to the laser diode array with pulse code modulation (PCM) on a small laser beam. Synchronizing pulses would be generated at the laser-diode array and transmitted to the receiver.

Unfortunately, laser-diode technology is not yet advanced enough to make the ideal system realizable. Laser diodes are expensive; single-pass laser-diode amplifiers are more expensive (presently available only by special order). Single-mode emissive power is small and schemes for coupling the laser master oscillator to amplifiers have not yet matured. Telemetry and digital switching technology are available.

Laboratory Experiment

The ideal system can be simulated by a laboratory experiment. With this experiment, we seek to verify some of the fundamental ideas of dynamic selection of laser array elements, check some of the scanning options, and define some important parameters. First, the laser array must be temporally coherent, which is best and most easily achieved with the use of one, single-mode, stabilized gas laser. Its beam will be split into 100 beams of approximately equal intensity. If we require about 10 milliwatts in each of the 100 beams, the output power of the gas laser should be roughly 1 watt. Small beam-splitter cubes could be used to effect the beam division. As shown in figure 5, the beam is sent through a series of 10 cubes. The first cube would reflect a tenth of the beam intensity; the second cube, a ninth; the third, an eighth, and so forth, to yield 10 beams of equal intensity propagating perpendicular to the master beam and parallel to each other. (The fine finish tolerances available for beam-splitter cubes would guarantee beam alignment and spacing.) Each of the 10 beams that were split from the master beam are, in turn, split into 10 equal intensity beams with another sequence of 10 splitter cubes. This produces 100 equal intensity beams of the same wavelength propagating parallel to each other (110 precision beam-splitter cubes are required). Each of the 100 beams could not be switched ON or OFF as a laser diode, but each could be blocked with a small fast-acting shutter. (Shutters are commercially available with 200-microsecond rise times and sizes approximating cube sizes.) The electromechanical action of the shutters would limit the performance of the array, since shutter operation cannot compare in speed with electrical switching. However, basic operation of the array could be proven, and performance could be extrapolated to higher performance components. Shutters made of Faraday rotators and polarizers would be faster, but their cost is excessive.

The far-field pattern of the 100 beams would be created at the focal point of a large-diameter lens through which all the beams pass. (See fig. 6.) At the focal plane of the lens, a fast scanning camera would be placed to monitor and record far-field patterns. The camera would be connected to a computer and would control the scan procedure, the scan rate, and shutter switching. It would also record the resultant far-field beam pattern. Part of the far-field pattern would be redirected with a partial reflector (piece of flat glass) to the beam sensor, a fiber light pipe connected to a sensitive photodiode. A computer algorithm will provide the scan control and decision making necessary for shutter actuation.

Development of this experimental configuration and measurements made with it could provide

1. Verification of the basic concepts of "dynamic diode selection"
2. A means to compare calculated far-field patterns with measured patterns
3. A way to check the performance of a start-up scan followed by a steady state scan
4. A testbed for checking the dynamic response of the laser system to sensor movements and correlate them with system variables (this could be critical for receiver movements on a mission)
5. The performance trade-offs with detailed phase mapping of the array
6. A confirmation of the advantages to be gained with overlapped phase distributions
7. An assessment of the practicality of creating and using phaser groups
8. Initial computer codes for this technology
9. A means of assessing scan rates, limiting array sizes, and temperature-related variations

Concluding Remarks

The production of powerful laser beams in the far field with quasi-coherent laser arrays is a feasible alternative to the use of fully coherent arrays. Such an array can be implemented simply by selecting which laser elements of the array are ON and which are OFF. (Laser array elements need only be temporally coherent with approximately parallel output beams.) The required power transmission can be achieved by adjusting the total number of laser elements in the array. Laser array elements are greatly simplified and less expensive. (No phase correcting device is required.) The degree of array coherence can be chosen and array lifetime can be extended.

By making the selection process dynamic (i.e., changing with time), such arrays are capable of active correction of time varying phase variations throughout the array. Modes for the selection process have been identified and nonuniform phase distribution has been discussed.

Dynamic, quasi-coherent arrays would be best implemented with laser diode elements. However, several associated technologies have not yet matured enough to make that practical. An alternative experiment is described which could demonstrate some of the salient features of the theory, help determine critical system parameters (e.g., scan rate versus mode and array size), and contribute to the development of required hardware and software.

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References

1. Williams, M. D.; and Conway, E. J., eds.: *Space Laser Power Transmission System Studies.* NASA CP-2214, 1982.
2. De Young, Russell J., ed.: *Second Beamed Space-Power Workshop.* NASA CP-3037, 1989.
3. Williams, M. D.: Laser Power Beams Obtained by the Dynamic Selection of Emitting Elements in an Array. *Appl. Opt.,* vol. 31, 1992.
4. Depatie, D. A., ed.: *Proceedings of DLTP Conference.* WL-CP-90-01, U.S. Air Force, Nov. 1990.
5. Born, Max; and Wolf, Emil: *Principles of Optics,* Fourth ed. Pergamon Press Inc., 1970.
6. Reynolds, George O.; DeVelis, John B.; Parrent, George B., Jr.; and Thompson, Brian J.: *The New Physical Optics Notebook: Tutorials in Fourier Optics.* SPIE Optical Engineering Press, c.1989.

(a) Coherent output.

(b) Far-field intensity pattern.

Figure 1. Coherent 7×15 element laser array.

(a) Emitting elements.

(b) Far-field pattern.

Figure 2. Selected laser elements with random phases (between $\pm\pi/2$ radians).

Figure 3. Variation of intensity at peak in far-field pattern with half-angle of coherence.

Figure 4. Random distribution of phasers over 2.5π radians. Upper right quadrant contains about twice as many phasers as any other quadrant.

Figure 5. Cube and shutter array. Only 3×3 elements of the 10×10 output array are shown.

Figure 6. Proposed experimental arrangement.