Beam quality of phased array lasers for long distance transmission

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Abstract

Far-field patterns of rectangular-symmetric array lasers were computed for various numbers of array elements, their pitch, and minimum spot size of each beam. The far-field patterns were evaluated in terms of a dimensionless main lobe radius and a fraction of beamed energy that is contained in the main lobe. As a result, the main lobe radius and energy fraction were found insensitive to the number of array elements but sensitive to a ratio of their pitch to the minimum spot size.

Introduction

In future space missions, acquisition of electric power is quite important. Beaming energy transmissions using a microwave or a laser beam have been attracting many interests.[1] Although laser beams are more advantageous in directionality than microwaves, there are mainly two obstacles in constructing a laser transmitter: In general, with the increase in power and size of a laser oscillator, it becomes more expensive and difficult to oscillate in a single transverse mode to produce optimum beam collimation.

An arrayed laser is one of the solutions to overcome these obstacles. However, in the case of a laser array, spatial coherence of the arrayed beam would be degraded because the distance between the array elements becomes inevitably larger than wavelength. Therefore, for the development of an arrayed laser beam system, it is important to know its combined diffraction pattern and dependency on geometric parameters of the array.

In this paper, effects of geometric parameters of a laser array on far-field diffraction pattern were numerically computed to evaluate a capability of a phased array lasers for long distance energy transmission.

Computational Models

Laser array source

In this analysis, an array of lasers was assumed to be composed of diffraction-limited Gaussian beams. The electric-field strength of a Gaussian beam at the beam waist is

$$E_{i,\mathrm{source}} = E_0 \exp\left[-\frac{(x-x_i)^2+(y-y_i)^2}{w_0^2}\right] \qquad (1)$$

where E_0 is electric-field amplitude, w_0 is a minimum spot size, and (x_i, y_i) is a center position of the i th element. A rectangular-symmetric array was assumed and analyzed as shown in Fig. 1. The pitch of array elements is Δ, and the number of elements is $n \times n$.

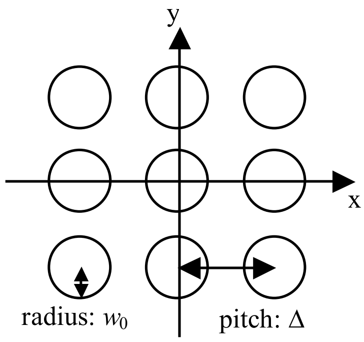

Fig. 1 Schematic of a rectangular array.

Far-field distribution

The electric-field distribution of a Gaussian beam in the far-field is

$$E_{i,\mathrm{far-field}} = \frac{E_0 w_0^2}{4\pi\lambda z}\exp\left[-\frac{w_0^2\left(\Omega_x^2+\Omega_y^2\right)}{4}\right] \times \exp\left[-j\left(x_i\Omega_x + y_i\Omega_y\right) - j\Phi\right] \qquad (2)$$

where

$$\Omega_x = -\frac{2\pi}{\lambda}\frac{x}{d}, \Omega_y = -\frac{2\pi}{\lambda}\frac{y}{d}$$
$$\Phi = \frac{2\pi}{\lambda}\left(z+\frac{x^2+y^2}{2d}\right)-\frac{\pi}{2} \qquad (3)$$
$$d^2 = x^2+y^2+z^2 .$$

Here, λ and z are a wavelength and a coordinate along the optic axis, respectively.

Intensity of combined laser beam

If laser beams are locked together in frequency to form a completely coherent phased array, intensity of resulting beam is expressed as

$$I_{\mathrm{coherent}} = \left|\sum_i E_i\right|^2 . \qquad (4)$$

If laser beams are totally incoherent, intensity of combined beam is

$$I_{\mathrm{incoherent}} = \sum_i \left|E_i\right|^2 . \qquad (5)$$

In this paper, all of the laser beams were assumed coherent and in phase. Several methods have been studied to combine laser beams coherently, such as MOPA/injection locking, coupled oscillators and external cavities.[2]

Evaluation of arrayed beam quality

The far-field patterns were evaluated in terms of a dimensionless beam radius of main lobe (W_{ML}/W_n), and a fraction of the beam energy that is contained in the main lobe η_{ML}. Beam radius of main lobe W_{ML} was defined as the first null beam radius as indicated in Fig. 2. W_n is a radius of the Gaussian beam having an emission area equivalent to the array, defined as

$$W_n = \frac{\lambda z}{\pi w_0 n}. \quad (6)$$

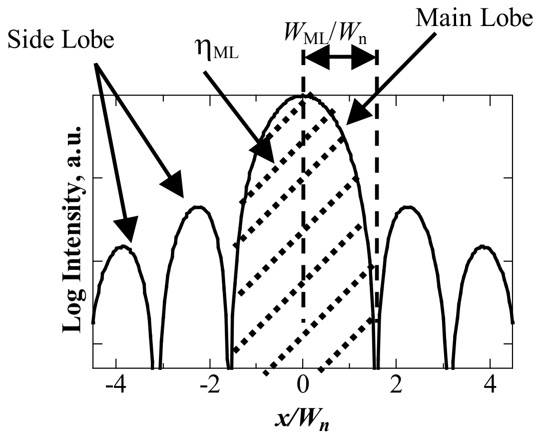

Fig. 2 Typical far-field pattern.

Results

Far-field patterns of arrays

Figure 3 shows far-field patterns of 10×10 rectangular arrays, with (a) Δ/w_0=2 (b) and Δ/w_0=5. Figure 3 (c) shows the intensity profile along the x axis, and its close-up near the main lobe. For Δ/w_0=5, η_{ML} is smaller than that for Δ/w_0=2 because several high-intensity side lobes exist, although the beam radius of the main lobe is narrower.

Therefore, when the pitch is extended, the radius of a receiver can be reduced, but η_{ML} is decreased.

Effects of *n*

W_{ML}/W_n and η_{ML} were calculated for various element number n and pitch Δ/w_0. Figure 4 shows the relationship between W_{ML}/W_n and n, and Fig. 5 shows the relationship between η_{ML} and n.

As shown in these figures, W_{ML}/W_n and η_{ML} are quite insensitive to n. In other words, a radius of a receiver is independent of the number of array elements but depends on the total emission area of the array. This also suggests that an array composed of small laser diodes can be utilized like a large-aperture laser if it has a large total emission area.

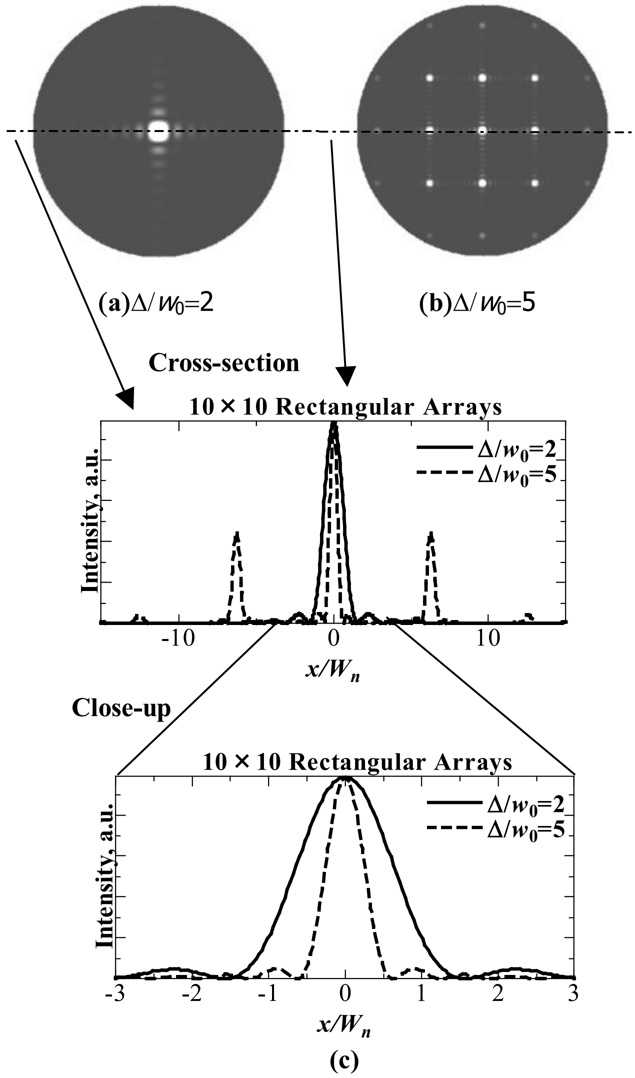

Fig. 3 Far-field patterns of 10×10 rectangular arrays.

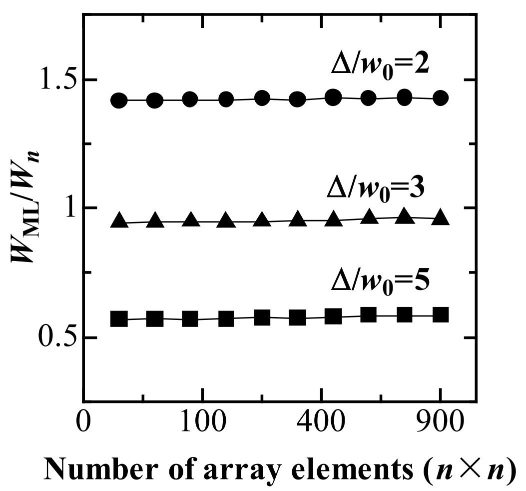

Fig.4 Relation of n and W_{ML}/W_n for Δ/w_0

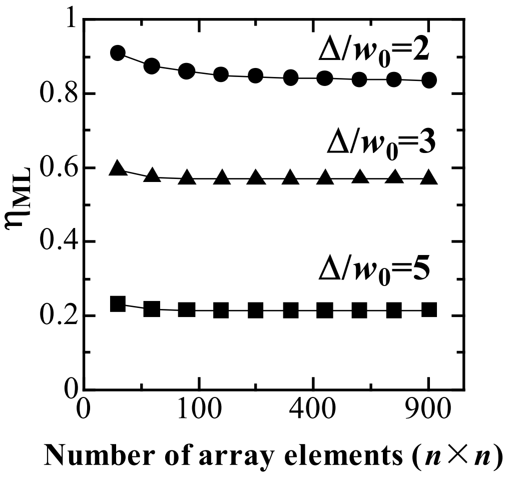

Fig. 5 Relationship of n and η_{ML} for Δ/w_0

Effects of Δ/w_0

Figure 6 shows the dependencies of W_{ML}/W_n and η_{ML} on Δ/w_0. Both W_{ML}/W_n and η_{ML} decreased with Δ/w_0. These dependencies are valid for any number of array elements because W_{ML}/W_n and η_{ML} were independent of the number of array elements as seen in Figs. 4 and 5.

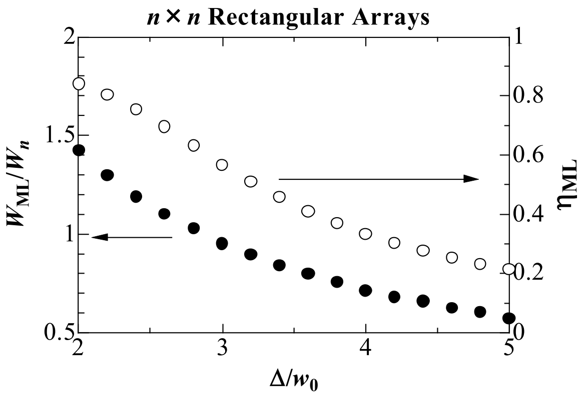

Fig. 6 W_{ML}/W_n and η_{ML} for Δ/w_0

Example of long distance energy transmission using a laser array

Using the computed results, a laser energy transmission of 1GW power at a distance of 40,000km was considered. Two array approaches, arrays of laser diodes and of glass lasers, were analyzed and compared.

Laser diode array

An element of a laser diode array was assumed as listed in Table 1. Output power of 2W is quite powerful for single-tip laser diode.

Table 1 Laser diode array

wavelength	808nm
output power per diode	2W
emission area:	100×1μm
minimum spot size w_0	100μm
distance ratio Δ/w_0	2.2

According to Fig. 6, W_{ML}/W_n=1.3 and η_{ML}=0.8 for Δ/w_0=2.2. Therefore, in order to transmit 1GW power, 25000×25000 lasers have to be clustered, and the corresponding transmitter size becomes 5.5×5.5m. W_n calculated using Eq. (6) is 4.2m and the diameter of receiver is estimated about 11m (See Fig. 7.) Figure 8 shows the intensity distribution on x axis at z=40,000km.

If laser beams are totally incoherent, a 200-km-diameter receiver will be required for the same diode laser arrray.

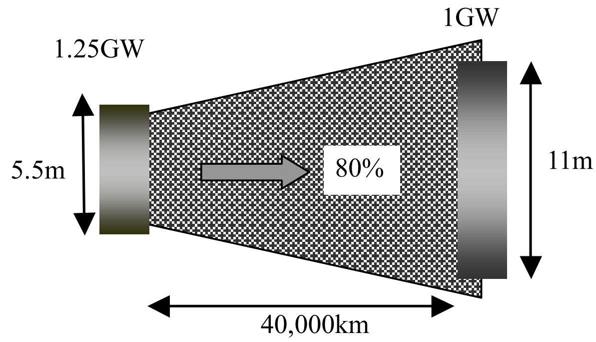

Fig. 7 Schematic of a long distance energy transmission using a coherent laser diode array

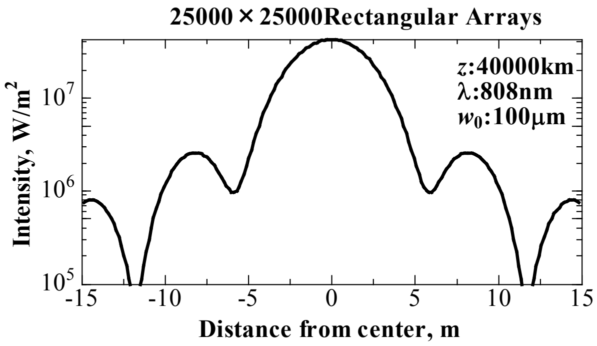

Fig. 8 Intensity distribution of the laser diode array at 40,000km

Glass laser array

Specifications of the assumed glass laser array are listed in Table 2.

Table 2 Glass laser array

wavelength	1.053μm
output power per laser	20kW
minimum spot size w_0	17.5cm
distance ratio Δ/w_0	2.2

In this case, 250×250 glass lasers are needed to be clustered and compose a 96m-squared array. The transmitter is larger than the laser diode array because of its low power density.

The field pattern at z=40,000km is shown in Fig 9. The pattern was not the far-field one because the ratio of the transmission distance to the transmitter scale is not so high enough. The receiver size becomes a 100-m-square as shown in Fig 10 and transmission efficiency is 80%.

If the lasers are assumed totally incoherent, the diameter of the receiver is 190m. Because the minimum spot size of each laser was large, the receiver's size of the incoherent array is only twice as large as that of the coherent array.

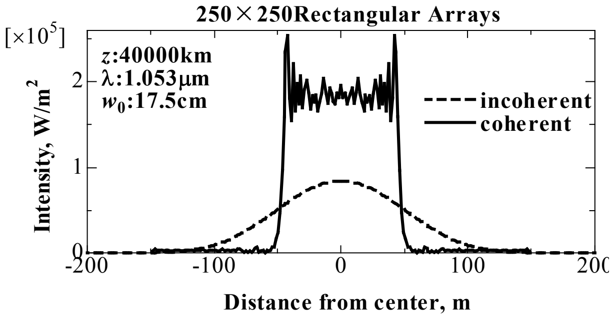

Fig. 9 Intensity distribution of the glass laser array at z=40,000km

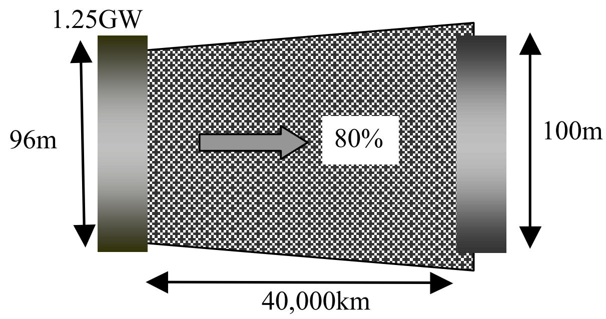

Fig. 10 Schematic of a long distance energy transmission using a coherent glass laser array

Summary

An analytical study on rectangular arrays for long distance energy transmission has been conducted. As a result, if an array had a constant emission area, both a main lobe radius and an energy fraction of the beam that is contained in main lobe were insensitive to the number of array elements. On the other hand, their dependence on a distance between array elements was found critical.

On the basis of these results, it was suggested that 1GW power can be transmitted from a 5.5×5.5m coherent laser diode array with Δ/w_0=2.2 to a 11-m-diameter receiver at a distance of 40,000km with the transmission efficiency of 80%.

References

[1] Glaser, P. E., "Power from the sun: its future," *Science*, Vol. 162(3856), pp. 857-861, 1968

[2] Salvi, T. C. and Dorato, S., "Coherent diode laser arrays", Proc. SPIE, Vol.3267, pp.91-97, 1998