

4 Wavefront Control Technologies

4-1 Nondiffracting Light Beams for Long Ranges

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A method of generating an unusual light beam, long range nondiffracting beam (LRNB) has been studied. The LRNB propagates over a long range keeping its narrow beam width as if it does not diffract, while general light beams spread by the diffraction effect. The new beam can be generated by a technique of wave front control, e.g., by a distorted concave spherical wave front that can be formed by a Galilean transmitting telescope with an eye-piece that has a spherical aberration. We will introduce some results of experiments as well as theoretical analyses of the LRNB generation using an unique optical system with a telescope and a laser.

Keywords

Light beam, Nondiffracting beam, Long range propagation, Wave front control, Spherical aberration

1 Introduction

Light beams including laser beams are used in many fields. We want to generate a narrow width light beam for a long range. This requirement occurs in many cases. Electromagnetic waves including light beams, however, spread by the diffraction effect. The beam divergence angle $\Delta\theta$ can be given by $\Delta\theta = \lambda/D$ (λ : wavelength, D : diameter of aperture). For getting a small divergence beam, the diameter of beam transmission must be large. But this condition contradicts to get a narrow beam. Consequently we can not generate a narrow light beam for a long range in general.

Recently, LRNB (Long Range Nondiffracting Beam) was found out [1]. The new light beam propagates over a long range keeping its narrow beam width as if it does not diffract. When we were performing an experiment of a laser (Ar laser) beam transmission

in free space using a transmission telescope of 10 cm diameter and a beam monitoring telescope of 50 cm diameter, we observed an unusual image with a striped pattern due to atmospheric back-scattering of the laser beam. The image provided an opportunity to examine this effect and found out the LRNB. It was caused by a narrow beam generation due to spherical aberration of the telescope used. A narrow beam was generated at the center of the original laser beam with 10 cm diameter [1]. The narrow beam acts as a nondiffracting beam which propagates over a long range.

The LRNB is similar to the Bessel beam. A near Bessel beam was theoretically studied and experimentally generated by Durnin [2] and Durnin et al. [3], and called nondiffracting beam or diffraction-free beam. The beam was generated by an optical system which consist of a ring slit and a lens. It was shown that the beam propagates up to $\sim 1\text{m}$ keeping its narrow beam width. By this method, one can

generate an extremely narrow beam (on the order of wavelength) without diffractive spreading. But energy concentration to the central region is quite small. Similar techniques have been applied to generate the same kind of diffraction-free beams [4]-[6]. Propagation ranges to as great as the order of 10 m have been realized so far. Studies of a light beam with narrow width have been previously carried out, e.g., studies of the axicon [7][8].

Distinctive features of the LRNB are that it propagates for a long range of ~ 100 m, $2 \sim 3$ km, ~ 10 km or longer (depending on transmission beam diameter) in free space and energy concentration to the central region is much larger ($\sim 30\%$). In this paper, we introduce the LRNB.

2 Concept of LRNB and Method of Generation

In many cases of light beam transmission, the light beam with collimation is used since the collimated beam condition is the best for long range light energy transmission.

In the case of a collimated beam transmission, the light of plane wave front is emitted (see Fig.1). The beam, however, spreads due to the diffraction effect.

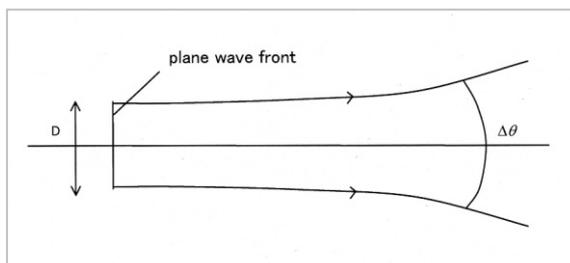


Fig.1 General collimated light beam

On the other hand, the LRNB can be generated by controlling the wave front to be a special shape. The shape should be a distorted spherical wave front in which its curvature reduces from the beam center to the edge at the aperture. As a concrete way of generation, there is a method to use a Galilean type telescope (see Fig.2) with spherical aberration. It is combination of a normal objective (convex

lens) and an eyepiece (concave lens) with a negative spherical aberration. By using the special transmitting telescope, a narrow core beam is generated at the center of the original beam (this core beam, i.e., main lobe corresponds to the LRNB; see Fig.3), and it propagates for a long range keeping its narrow beam width.

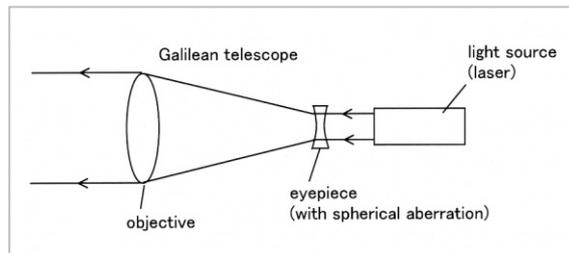


Fig.2 Optical system for the LRNB generation

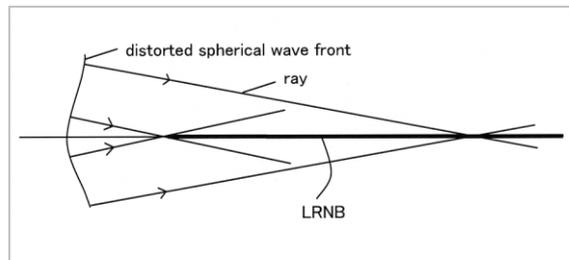


Fig.3 Concept of the LRNB generation

3 Examples of LRNB Generation : Computer Simulations and Experiments

Next we show some examples of computer simulations and real experiments for generation of the LRNB. Exact analyses of the non-diffracting light beam can be performed by using the Huygens-Fresnel diffraction theory [9][10]. The light amplitude $U(P)$ at point P can be formulated as an integral:

$$U(P) = c \iint A(\xi, \eta) \exp[-ikl(\xi, \eta)] d\xi d\eta, \quad (1)$$

where ξ and η are coordinates in the aperture of laser beam transmission, $A(\xi, \eta)$ is the amplitude at each point (ξ, η) the aperture, k is the wave number ($=2\pi/\lambda$), and $l(\xi, \eta)$ is the distance between P and points (ξ, η) . Then the light intensity $I(P)$ at P is

$$I(P) = |U(P)|^2. \quad (2)$$

Next we extend the formulation from the plane wave front to general curved wave fronts. The distance l between points P and Q on the wave front in the aperture is approximately

$$l = z + \frac{x^2 + y^2}{2z} - \frac{x\xi + y\eta + z\zeta}{z} + \frac{\xi^2 + \eta^2 + \zeta^2}{2z}, \quad (3)$$

where (x, y, z) and (ξ, η, ζ) are the coordinates of points P and Q, respectively. The third coordinate ζ corresponds to wave front shape $h(\rho)$, so that we may write

$$\zeta = h(\rho), \quad (4)$$

where ρ is radial distance defined as $0 \sim 1$. Because of the axial symmetry of the emitted laser beam, the Fresnel integral (1) can be reduced to

$$u(P) = 2\pi a^2 c \int_0^1 A(a\rho) J_0\left(r \frac{k}{z} a\rho\right) \exp\left[-i\left(\frac{k}{2z} a^2 \rho^2 - k\zeta\right)\right] \rho d\rho, \quad (5)$$

where a is radius of the aperture, z and r [$= (x^2 + y^2)^{1/2}$] are coordinated of points P and J_0 is the Bessel function of order zero (For details, see Reference 1.). Here the phase factor derived from z and $r^2/2z$ is omitted as is generally done (because it is ineffective) and $\zeta \ll z$ is assumed. The constant c is determined by condition $\int I(P) dx dy = 1$.

The LRNB was found out when we have been conducting, research of a laser beam

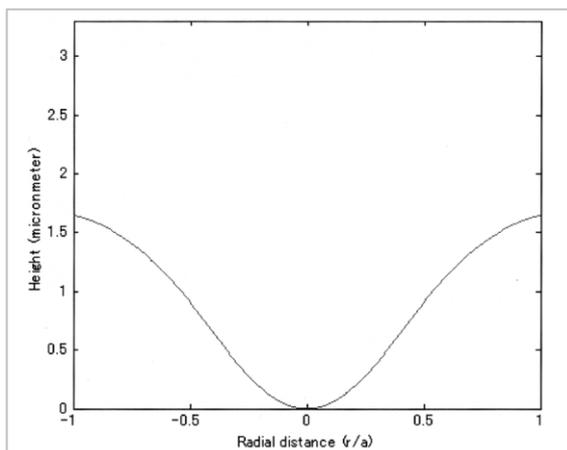


Fig.4 Example of wave front profile

(argon-laser) transmission by a Galilean telescope of 10 cm diameter. By this reason, we will introduce at first generation of a LRNB of 10 cm diameter. The focal length f of the telescope's objective is 40 cm, thus $F (=f/D)$ is 4 and that of eyepiece is set to be 5 cm.

Figure 4 shows a wave front which was formed by the Galilean telescope with eyepiece's spherical aberration of $580 \mu\text{m}$. The wave front curvature reduces from the center (optical axis) to the aperture edge. Shape of the wave front can be controlled by changing distance between object and eyepiece of the telescope. For example, outside shape can be linear, where more exact nondiffracting beam is generated although range is reduced [1]. Figure 5(a) is an example of computer simulation, i.e., light beam pattern along the optical axis, where a condition of using a light source of Nd:YAG laser ($\lambda = 0.53 \mu\text{m}$) and wave front shape of Fig.4 is assumed. Figure 5(b) is a

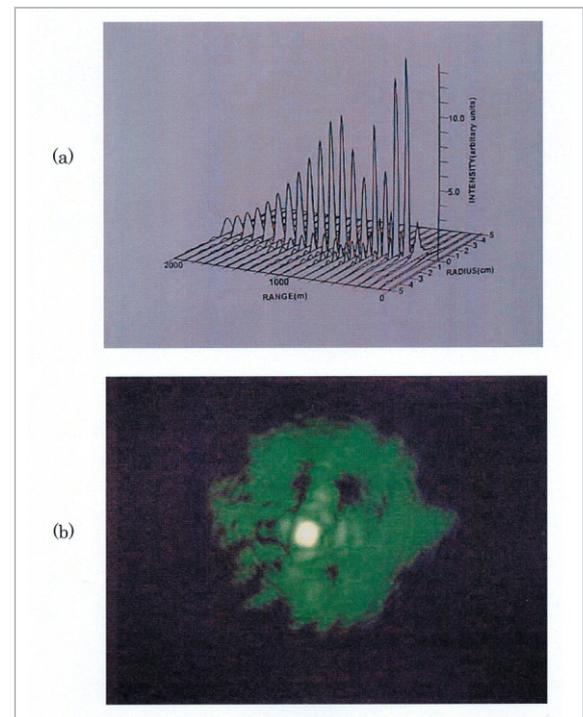


Fig.5 LRNB generation by a telescope of 10cm diameter

- (a) Computer simulation of propagating laser beam pattern. LRNB is generated at the center of original beam with 10cm diameter.
- (b) Example of the LRNB photograph (distance 500m). Central bright spot corresponds to the LRNB.

photograph of the really generated light beam, i.e., the propagating laser beam pattern taken at ~ 500 m distance. The central bright spot corresponds to the LRNB. The side-lobe area is disturbed by atmospheric turbulence.

Next we introduce generation of the LRNB targeting a shorter range of several 100 m distance. Figure 6(a) shows an example of the LRNB generation using a telescope of 2.5 cm diameter and 10 cm focal length. Here $\lambda = 0.6328$ (He-Ne laser) is assumed. The figure shows the propagating laser beam pattern along the optical axis as we showed in Fig.5(a). A photograph of the propagating laser beam pattern taken at ~ 100 m distance is shown in Fig.6(b).

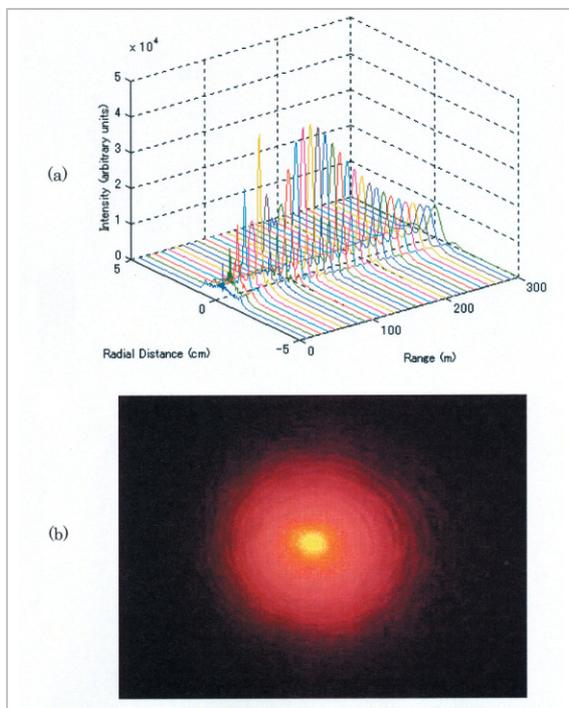


Fig.6 LRNB generation by a telescope of 2.5cm diameter

- (a) Computer simulation of propagating laser beam pattern. LRNB is generated at the center of original beam with 2.5cm diameter.
- (b) Example of the LRNB photograph (distance 100m). Central bright spot corresponds to the LRNB.

For a longer range LRNB generation, we produced a telescope of 20 cm diameter and 80 cm focal length keeping F number 4 as the above two cases. In this case, we used a com-

pact Nd:YAG laser ($\lambda = 0.53 \mu\text{m}$) for a light source of the LRNB generation. Figure 7(a) shows an example of computer simulation of propagating light beam pattern up to 10 km. Very recently we conducted the LRNB generation/transmission experiment using the optical system. A photograph of the laser beam pattern taken at a tower which distance is 4.5 km and height is ~ 150 m, is shown in Fig.7(b). It is to be noted that the side-lobe area is strongly disturbed by atmospheric turbulence.

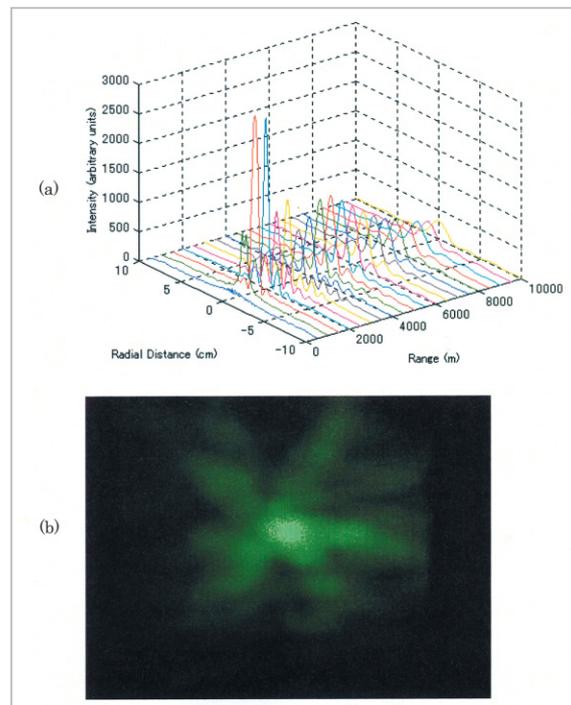


Fig.7 LRNB generation by a telescope of 20cm diameter

- (a) Computer simulation of propagating laser beam pattern. LRNB is generated at the center of original beam with 20cm diameter.
- (b) Example of the LRNB photograph (distance 4.5km). Central bright spot corresponds to the LRNB.

4 Characteristics of the LRNB

During past experiments of LRNB propagation, we found out several characteristics of the LRNB. At first, the central core beam (main lobe) which corresponds to the LRNB is much more stable against atmospheric turbu-

lence than the surrounding region (side lobes). Furthermore the LRNB is more stable than general collimated or focused beams. The fact has been reported quantitatively [11]. Secondly, it was become clear from computer simulations that, over a long range, the main lobe width is smaller than that of normal optics with diffraction-limit [12]. This means optical system of the LRNB has a higher resolution than normal optics with diffraction-limit. Thirdly, we can generate a short range LRNB by a small optical system and a long range LRNB by a large one. For example, a few 100 m range by a telescope of 2~3 cm diameter, several km range by ~10 cm diameter and several 10 km range by ~50 cm diameter. These are summarized as

- 1) LRNB propagates for a long range keeping its narrow beam width,
- 2) LRNB is more stable than general beams against atmospheric turbulence,
- 3) For a large region of distance, super high-resolution (higher than diffraction-limit) can be obtained,
- 4) Short and long range LRNBs can be respectively generated by small and large optical systems.

5 Application of LRNB optical system to imaging

We have described about LRNB generation by light beam transmission showing some examples of generated LRNBs by an optical system, up to the 3rd section. The optical system is a Galilean telescope with an eyepiece that has a spherical aberration. If we use the LRNB optical system for reception of light, we can perform imaging. Thus, in this section, we briefly add description about application of the LRNB optical system to imaging.

By a combination of the LRNB optical system and a camera, imaging is possible. In this case, focal depth become much deeper than imaging by general camera with a lens of equal focal length. Examples of computer simulation are shown in Fig.8 (a) and (b). They are comparison of focus pattern (light

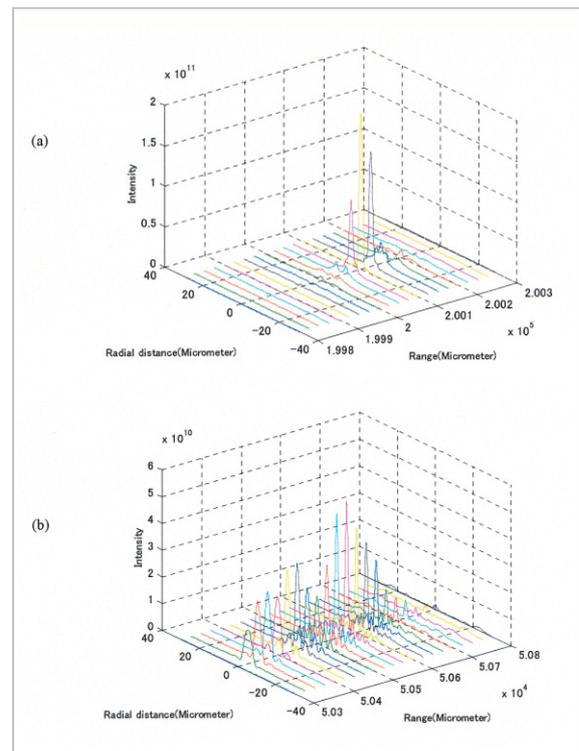


Fig.8 Focus patterns of imaging : Computer simulations

- (a) By a general tele-lens ($D : 50\text{mm}$, $f : 200\text{mm}$), where object's distance 500m is assumed.
- (b) By a LRNB optical system (using the same objective as the tele-lens of (a)), where object's distance 500m is assumed.

intensity profiles at focal region) between imaging by a general camera with a lens : $D = 5\text{ cm}$, $f = 20\text{ cm}$ and a LRNB optical system with the same lens. Here, object's distance of 500 m is assumed. In Fig.8 (a), a tele-lens of $f200$ ($f = 200\text{ mm}$, $D = 50\text{ mm}$) is used for a general camera lens. On the other hand, in (b), combination of a telescope (an objective with the same lens and an eyepiece with -50 mm focal length and spherical aberration of $580\mu\text{m}$) and a camera with 50 mm focal length, is assumed.

In Fig.8 (a) and (b), we can easily understand that focal depth of (b) (by a special optical system based on the LRNB) is much deeper than that of (a) (by a general optical system).

If focal depth is enough deep, we can get images of objects existing over a wide range by a fixed focus, i. e., without changing focal length, while focal length must be changed

following distances of objects (otherwise images are blurred). This fact has been shown by our real imaging experiments.

6 Conclusions

In this paper, an unique light beam LRNB was introduced. The characteristics of the new beam, i.e., propagation for a long range keeping its narrow beam width and others were demonstrated showing results of real experiments as well as computer simulations. We showed results of LRNB generation using telescopes with diameter of 2.5 cm, 10 cm and

20 cm for ranges of a few 100 m to 10 km. If we use smaller optical systems, we can generate LRNBs for shorter ranges and larger systems for longer ranges.

Many results we have obtained so far show that the LRNB should be applicable to wide fields.

Acknowledgements

The authors thank Y. Michino, H. Iida, Y. Nakajima of the Shin-Nihon-Kagaku Production Co. and S. Yoshikado of SCAT for their assistance with the experiments.

References

- 1 T. Aruga, "Generation of long range nondiffracting narrow light beams", *Appl. Opt.*, 36, pp. 3762-3768, 1997.
- 2 J. Durnin, J. J. Miceli, Jr., and H. J. Everly, "Exact solutions of nondiffracting beams. I. The scalar theory", *J. Opt. Soc. Am.*, A4, pp. 651-654, 1987.
- 3 J. Durnin, "Diffraction-free beams", *Phys. Rev. Lett.*, 58, pp. 1449-1501, 1987.
- 4 K. Uehara and H. Kikuchi, "Generation of nearly diffraction-free laser beams", *Appl. Phys. B* 48, pp. 125-129, 1988.
- 5 A. J. Cox and J. D'Anna, "Nondiffracting beam from a spatially filtered Fabry-Perot resonator", *Opt. Lett.* 17, pp. 232-234, 1992.
- 6 J. Turnen, A. Vasara, and A. T. Friberg, "Holographic generation of diffraction-free beams", *Appl. Opt.* 27, pp. 3959-3961, 1998.
- 7 H. McLeod, "The axicon : a new type of optical element", *J. Opt. Soc. Am.* 44, pp.592-597, 1954.
- 8 S. Fujiwara, "Optical properties of conic surfaces. I. Reflecting cone", *J. Opt. Soc. Am.* 52, pp. 287-292, 1962.
- 9 M. Born and E. Wolf, *Principle of Optics*, Pergamon, Oxford, UK, 1975.
- 10 N.G. Van Kampen, "The method of stationary phase and the method of Fresnel zones", *Physica*, 24, pp. 437-444, 1958.
- 11 T. Aruga, S. W. Li, S. Yoshikado, M. Takabe, and R. Li, "Nondiffracting narrow light beam with small atmospheric turbulence-influenced propagation", *Appl. Opt.*, 38, pp. 3152-3156, 1999.
- 12 T. Aruga and S. W. Li, "Super high resolution for long-range imaging" *Appl. Opt.*, 38, pp. 2795-2799, 1999.



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