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Coherent beam combining of 2-μm fibre lasers*

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Abstract. **Coherent beam combining of 2-μm fibre lasers is studied numerically. Such lasers are a suitable candidate for creation of a beam combining module due to their higher nonlinear effect and optical damage threshold compared to their 1-μm counterparts. The calculations results show that radiation of a 1-μm fibre laser has a better focusing property in free-space due to a smaller wavelength, whereas a 2-μm laser beam has a better focusing capability in the target-plane under conditions of real atmospheric turbulence.**

Keywords: *fibre laser, coherent combining of laser beams, laser beam focusing.*

1. Introduction

Coherent beam combining of fibre lasers can efficiently solve the problem of power limitation in a single laser, which has made it an object of intense research recently. Compactness of fibre lasers/amplifiers makes them a perfect candidate for beam summation. For the time being, almost all previous studies have focused on coherent combining of beams from 1-μm Yb^{3+}-doped fibre lasers. Nevertheless, scaling the output power of such lasers is quite a challenge due to the nonlinear effect and optical damage arising in them [1]. At the same time, a 2-μm Tm^{3+}-doped fibre laser presents good solution for creating a beam combining module due to its higher nonlinear effect and optical damage threshold compared to its 1-μm counterpart [2, 3]. Such a laser may finally become an ideal module for a high energy laser system made up of an array of fibre lasers.

Recently, a thulium-doped fibre laser (TFL), which emits near 2 μm, has lead to the revolution in high-power fibre laser technology [4–10]. A TFL can find wide application in medicine, lidars, material processing, and nonlinear frequency conversion to mid-IR wavelength range. Radiation of this laser (1.9–2.1 μm) falls into the 'eye-safe' wavelength range, giving it potential advantages over 1-μm fibre lasers. The power scaling of Tm-doped fibre lasers has rapidly gained momentum in recent years. Goodno et al [3] realised a single-mode, single-frequency TFL amplifier with an output power of over 600 W, and Ehrenreich et al. [11] demonstrated a two-stage TFL amplifier with an output power exceeding 1 kW. Nevertheless, further increasing the output power will face great challenges caused by such nonlinear effects as stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS). Because the requirement to increase the brightness of TFLs is important for many applications, coherent beam combining of TFLs is also a key technology that deserves to be investigated for the following reasons.

Firstly, high-power 2 μm fibre laser systems can benefit from operating at eye-safer wavelengths, which indicates that the permissible power transmission in free space can be several orders of magnitude greater than at 1 μm. Besides, the excellent transmission property of TFLs in turbulent atmosphere has been validated [12]. Secondly, due to a longer wavelength, it is possible to predict a higher SBS threshold of TFLs compared with 1-μm Yb-doped fibre lasers [11, 12]. This makes it possible to scale the power of a single fibre laser. Thus, if a high-average-power fibre laser system is to be designed, much less laser channels are required if a TFL is employed instead of a Yb-doped fibre laser, which could make the laser system less complex and more compact. Although a 1-μm fibre laser has a better power focusing property in free-space due to a smaller beam divergence angle of a shorter wavelength, a 2-μm laser beam has a longer coherence length when propagating in turbulent atmosphere, which may be an advantage for practical use.

In this paper, we study in detail the trade between the smaller beam divergence angle and longer coherence length. We hope to get some instructive conclusion for practical realisation of a high-power fibre laser system.

2. General formulas

We consider a ring distributed laser array shown in Fig. 1. This distribution ensures a high fill factor value and approximates well a circular beam. The ring distributed array consists of a central element and elements whose centres lie on several concentric rings. All the elements are located in such a way that the distance between their centres is the same and equal to d. An array with N rings will contain M lasers. Suppose that each laser beam has a Gaussian single-mode field distribution. The beam waist of each laser is w_0. We define the vacancy factor $f = (d - 2w_0)/w_0$ to describe the compactness of the array: the smaller the value of f the more compact the array. The diameter of the whole laser array is $D = 2Nd + 2w_0$. We assume that the laser array is located at the source plane ($z = 0$). The laser beams propagate along the z axis in the Cartesian coordinate system. The field distribution for the coherently combined laser array at the source plane can be written as

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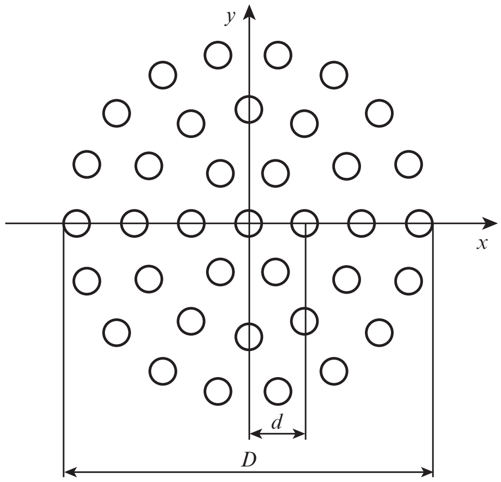

Figure 1. Scheme of the laser beam array.

$$E(\xi,\eta,0)=\sum_{m}^{M}E_m(x_m,y_m,0),\tag{1}$$

where $E_m(x_m, y_m, 0)$ is the field of the mth laser beam whose centre is located at the point $(x_m, y_m, 0)$. By using the extended Huygens–Fresnel principle, the average intensity distribution for coherently combined beams at the receiver plane with a propagation distance $z = L$ can be expressed as

$$\langle I(x,y,z)\rangle=\frac{k^2}{(2\pi L)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}E(\xi,\eta,0)E^*(\alpha,\beta,0)$$

$$\times\exp\left\{\frac{\mathrm{i}k}{2L}[(x-\xi)^2+(y-\eta)^2-(x-\alpha)^2-(y-\beta)^2]\right\},$$

$$\times\langle\exp[\psi(\xi,\eta,x,y)+\psi^*(\alpha,\beta,x,y)]\rangle\mathrm{d}\xi\mathrm{d}\eta\mathrm{d}\alpha\mathrm{d}\beta,\tag{2}$$

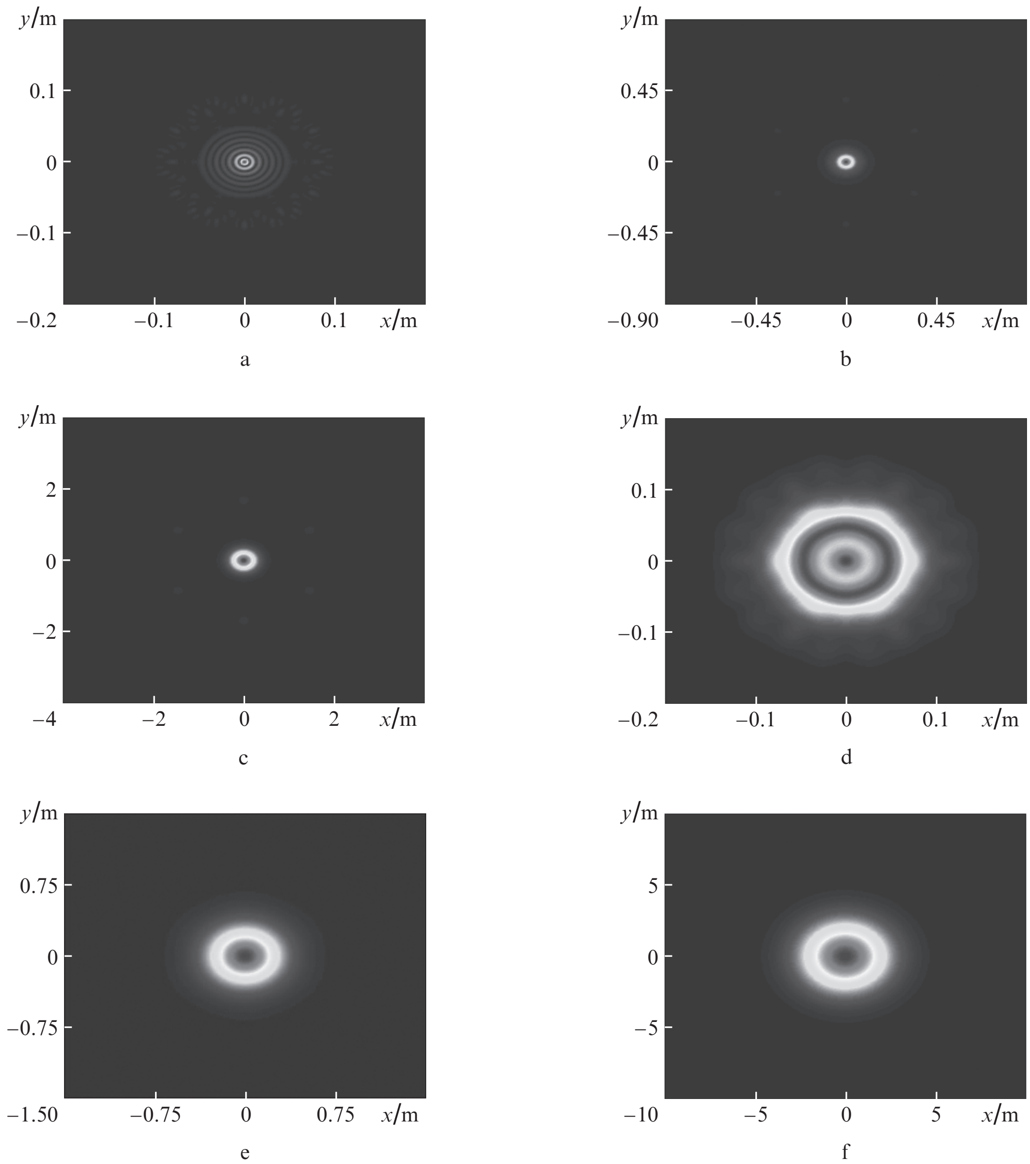

Figure 2. Intensity profiles for the beam array at different atmospheric conditions and different propagation distance: (a) $C_n^2 = 1\times10^{-15}$ m$^{-2/3}$, $z = 1$ km, (b) $C_n^2 = 1\times10^{-15}$ m$^{-2/3}$, $z = 5$ km, (c) $C_n^2 = 1\times10^{-15}$ m$^{-2/3}$, $z = 20$ km, (d) $C_n^2 = 5\times10^{-14}$ m$^{-2/3}$, $z = 1$ km, (e) $C_n^2 = 5\times10^{-14}$ m$^{-2/3}$, $z = 5$ km and (e) $C_n^2 = 5\times10^{-14}$ m$^{-2/3}$, $z = 20$ km.

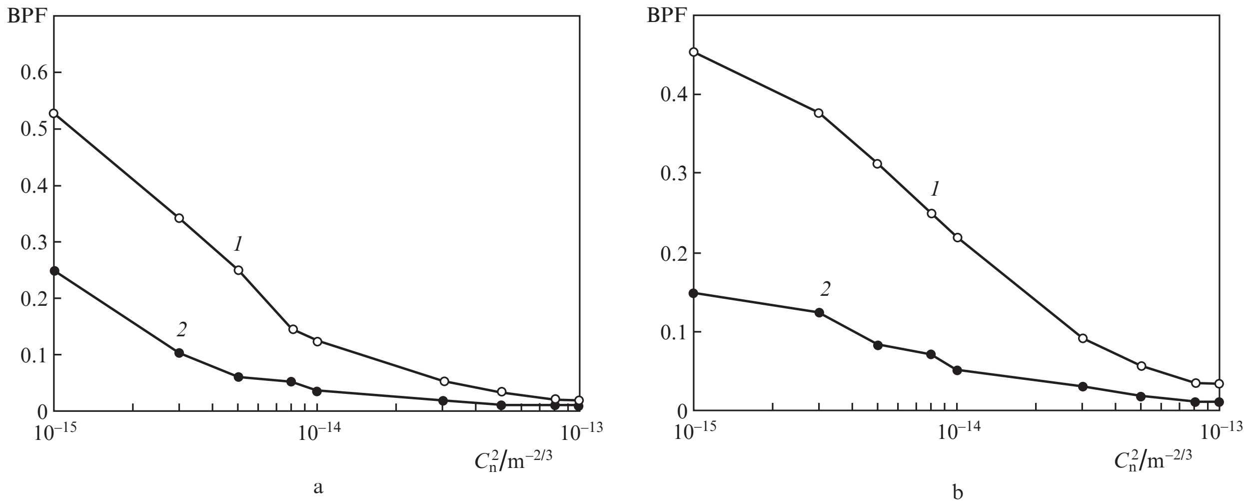

Figure 3. Beam propagation factors (BPFs) for (*1*) 2-μm laser and (*2*) 1-μm laser arrays at (a) z = 5 and (b) 10 km.

where k is the wave number; $\psi(\xi,\eta,x,y)$ is the random part of the complex phase of a spherical wave that propagates from the source point to the receiver point; the angle brackets indicates the ensemble averaging over the medium statistics covering the log-amplitude and phase fluctuations due to the turbulent atmosphere. In this paper, the Kolmogorov spectrum and a quadratic approximation of the 5/3 power law for Rytov's phase structure function is employed. The last term in the integrand of Eqn (2) can be written as [13, 14]

$$\langle \exp[\psi(\xi,\eta,x,y) + \psi^*(\alpha,\beta,x,y)]\rangle$$
$$= \exp\{-[(\xi-\alpha)^2 + (\eta-\beta)^2]/\rho_0^2\}. \qquad (3)$$

Here $\rho_0 = (0.545 C_n^2 k^2 L)^{-3/5}$ is the coherence length of a spherical wave propagating in the turbulent atmosphere with C_n^2 being the structure constant. From this formula we can see that the coherence length for a 2-μm laser is longer than that of its 1-μm counterpart in the case of the same structure constant (i.e., the same intensity of turbulence), which indicates that the propagation property of a 2-μm beam is less affected by the turbulence.

The effect of propagation in turbulent atmosphere can be characterised by the beam propagation factor (BPF) [15, 16], which is defined as the laser output power in a specified far-field bucket divided by the total output power radiating from the effective near-field exit aperture of the laser beam. The far field bucket is defined as $A_{dl} = (\pi/4)(\theta_{dl} z)^2$, which is a diffraction-limited bucket ($\theta_{dl} = 2.44\lambda/D_{eff}$, where D_{eff} is the effective exit aperture of the laser beam, namely, the diameter of the whole laser array D). In general, the BPF is smaller than unity; however, the closer the factor to unity, the better propagation result one gets.

3. Numerical calculations

In this section, we study numerically the propagation performance of a coherently combined 2-μm fibre laser array. The parameters of the coherently combined laser array used for calculations are follows: λ = 2.0 μm, w_0 = 1 cm, f = 0.5, d = 2.5 cm, N = 3, M = 37. The calculations are performed by direct programming. The intensity profile for the beam array under different atmospheric conditions at different propagation distances is computed and plotted in Fig. 2. It is found that the beam intensity profile is affected by the propagation distance and the intensity of the turbulence. The beam profile gradually evolves into a fixed pattern with increasing propagation distance.

The calculated values of the BPF, characterising the change in the beam quality upon its propagation in atmosphere are presented in Fig. 3. Except for the laser wavelength, the other parameters are the same as those used in Fig. 2. One can see that the beam propagation property of a 2-μm laser exceeds that of its 1-μm counterpart at different propagation distances and different turbulences, which can be attributed to the longer coherence length of 2-μm lasers that suppresses the influence of the turbulence.

It has to be pointed out that we did not take into account the atmosphere transparency for Tm-fibre laser emission in the numerical study, although the spectral band of its emission contains many absorption peaks [12]. So in practical use, the laser wavelength should be selected carefully (for example, 2.04 μm) to ensure a maximal atmosphere transparency for laser radiation. As for some absorption peaks, such as near 1.95 and 2.0 μm, these spectral bands should not be employed for long-range power beaming use.

4. Conclusions

We have presented a detailed analysis of coherent beam combining of 2-μm laser beams. Although the 1-μm fibre laser has a better power focusing property in free-space due to a smaller beam divergence angle of a smaller wavelength, we have found that when propagating in turbulent atmosphere, coherent beam combining of 2-μm laser beams does not only benefit from the maximal output power, but also has a better power focusing capability in the target-plane under real atmospheric turbulence conditions.

References

1. Dawson J.W. et al. *Opt. Express*, **16** (17), 13241 (2008).
2. Moulton P.F. et al. *IEEE J. Sel. Top. Quantum Electron.*, **15** (1), 85 (2009).
3. Goodno G.D. et al. *Opt. Lett.*, **34** (8), 1204 (2009).
4. http://www.nufern.com/library/item/id/169/.

5. Geng J., Wang Q., Luo T., Jiang S., Amzajerdian F. *Opt. Lett.*, **34**, 3493 (2009).
6. Zhang Y.J., Wang W., Song S.F., Wang Z.G. *Laser Phys. Lett.*, **6**, 723 (2009).
7. Meleshkevich M., Platonov N., Gapontsev D., Drozhzhin A. *Proc. Eur. Conf. Lasers Electro-Optics* (Munich, 2007).
8. Moulton P.F., Rines G.A., Slobodtchikov E.V., Wall K.F., Frith G., Samson B., Carter A.L.G. *IEEE J. Sel. Top. Quantum Electron.*, **15**, 85 (2009).
9. Zhang Z., Shen D.Y., Boyland A.J., Sahu J.K., Clarkson W.A., Ibsen M. *Opt. Lett.*, **33**, 2059 (2008).
10. Moulton P.F. *Poc. Conf. on Laser and Applications in Science and Engineering (LASE 2008)* (2008) Paper 6873-15.
11. Ehrenreich T., Leveille R., Majid I., Tankala K., Rines G., Moulton P.F. *Proc. SPIE Int. Soc. Opt. Eng.*, **7580**, 758016 (2010).
12. McComb T., Shah L., Sims R.A., Sudesh V., Szilagyi J., Richardson M. *Proc. Conf. on Lasers Electro-Optics* (2009).
13. Cai Y., Chen Y., Eyyuboglu H.T., Baykal Y. *Appl. Phys. B*, **88**, 467 (2007).
14. Wang S.C.H., Plonus M.A. *J. Opt. Soc. Am.*, **69**, 1297 (1979).
15. Zhou P., Liu Z., Xu X., Chen Z. *Appl. Opt.*, **47** (18), 3350 (2008).
16. http://www.darpa.mil/Our_Works/MTO/Programs/Architecture_for_Diode_High_Energy_Laser_Systems_(ADHELS).aspx.