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Side lobe suppression of a Bessel beam for high aspect ratio laser processing

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ABSTRACT

Bessel beams can be used for high aspect ratio laser drilling and for eliminating the need to precisely position materials along the propagation direction during laser drilling and cutting. However, Bessel beams have side lobes that can damage the materials subjected to these beams. This paper discusses optical suppression of side lobes. A method is proposed to suppress these side lobes, and the method is based on interference between two Bessel beams with different wave vectors. The effectiveness of this method is confirmed both theoretically and experimentally by realizing a superposed Bessel beam; using a He–Ne laser ($\lambda = 633$ nm) and an annular binary aperture placed in front of a convex lens, this beam has a $1/e^2$ radius of 44 μm.

1. Introduction

Well known as non-diffracting waves, Bessel beams are propagation invariant and do not suffer from diffraction spreading, unlike other beams [1,2]. Many applications based on the unique characteristics of Bessel beams have been studied [3–5]. During laser drilling and cutting, Bessel beams eliminate the need to precisely position materials along the propagation direction, which is vital in ordinary systems [6]. Another possible application for Bessel beams includes high aspect ratio laser drilling [6,7]. However, Bessel beams have side lobes that damage the materials subjected to these beams [8]. Matsuoka et al. [9] studied the environmental conditions required to reduce damage caused by side lobes. This paper explores optical suppression of side lobes. In this study, a suppression method is proposed, and its effectiveness is confirmed both theoretically and experimentally.

2. Side lobe suppression by superposition of two Bessel beams

2.1. Theory and results

Consider a Bessel beam propagating along the z direction; this beam is a superposition of plane waves propagating with angle θ along the z-axis. The beam is represented by the following equation:

$$u(r) = A\exp(ik_z z)J_0(k_r r) \quad (1)$$

where A is the amplitude, while k_z and k_r are the wavenumbers of the z component and the radial component respectively. The beam intensity profile given by the square of $u(r)$ is shown in Fig. 1, and the intensity is normalized. The first, second, and third side lobes are, respectively, 16%, 9%, and 6% of the maximum intensity at the center. These side lobes often damage materials during laser drilling.

In order to suppress side lobes, Bessel beams 1 and 2 – whose wavenumbers have different z components – are superposed such that the side lobes interfere with each other, and the peak values are thereby reduced. The superposition of these beams, a superposed Bessel beam (SBB) is represented as follows:

$$u(r) = A_1\exp(ik_{z1}z)J_0(k_{r1}r) + A_2\exp(ik_{z2}z)J_0(k_{r2}r) \quad (2)$$

where suffixes 1 and 2 represent the respective beams. Suppose $\exp(ik_{z1}z)$ and $\exp(ik_{z2}z)$ – the phase factors in Eq. (2) – are equal at position P on the z-axis. Then, neglecting common phase factors, the amplitude of the SBB is simply given by

$$u(r) = A_1J_0(k_{r1}r) + A_2J_0(k_{r2}r) \quad (3)$$

Here, amplitudes A_1 and A_2 are optimized such that the following integral is the minimum:

$$\int_{r_{\min}}^{r_{\max}} \left|A_1J_0(k_{r1}r) + A_2J_0(k_{r2}r)\right|^2 dr \quad (4)$$

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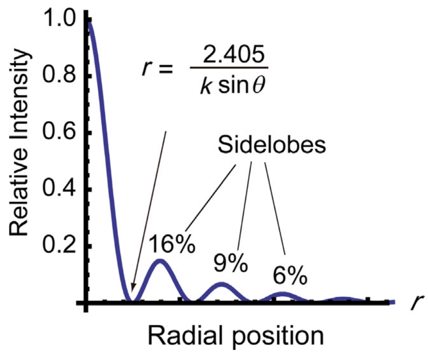

Fig. 1. Intensity profile of Bessel beam. The first side lobe reaches 16% of the maximum intensity.

The lower integral limit, $r_{\min}$, is chosen to equal the desired beam radius, r_0; for $r \geq r_0$, the beam intensity is zero. The upper integral limit, $r_{\max}$, is chosen to cover the suppression area. Because the phase factors change with z, the factors coincide with each other repeatedly and the period p is given by [10].

$$p = \frac{2\pi}{\left|k_{z1} - k_{z2}\right|} \approx \frac{4\pi k}{\left|k_{r1}^2 - k_{r2}^2\right|} \tag{5}$$

The optimized beam profile is invariant over large distances when the difference between k_{z1} and k_{z2} is small. In the experiments described later, the beam profiles were almost invariant over the lengths of from 1/6 to 1/3 of the periods given by Eq. (5).

In this paper, two cases are studied. In case 1, all side lobes are suppressed, and in case 2, only the side lobe near the main lobe is suppressed.

Case 1. In the calculation, the upper limit is set equal to $5r_0$. The optimization results obtained by setting larger upper limits showed no significant improvement in side lobe reduction. The numerical optimization of Eq. (4) yields $A_1 = 0.434$, $A_1 = 0.566$, $k_{r1} = 1.354/r_0$, and $k_{r2} = 2.402/r_0$. Fig. 2(a) shows the amplitude of the optimized beams. Bessel beams 1 and 2 and the superposition of the two beams (the SBB) are indicated in blue, green, and red, respectively. Fig. 2(b) shows the intensity distribution of the SBB. The side lobe near the center, which is observed in Fig. 1, is reduced to 4.3% of the maximum intensity. Nevertheless, new small side lobes appear in the outer region where $r/r_0 = 5.5$ and 7.

This reduction in the occurrence of side lobes comes as a trade-off with the propagation–invariant characteristics of the Bessel beam because the SBB periodically changes its profile, as described above. Fig. 3 shows the theoretical relationship between the period and the ratio of the side lobe to the peak at the center of the beam. The calculation was performed as follows:

Firstly, optimization of Eq. (4) was performed with the additional condition that $k_{r2} - k_{r1}$ constant. Then the period was calculated from $k_{r1}$and k_{r2} using Eq. (5). As shown in Fig. 3, the period is normalized by the period for which side lobe reduction reaches its maximum. In Fig. 3 (a), blue lines represent the ratio of the maximum side lobe to the peak, and the red line represents the ratio of the first side lobe (the side lobe adjacent to the main lobe) to the peak. The maximum side lobe is also the first side lobe when the period is more than unity. As the period increases, the ratio of the maximum side lobe approaches 16%, which is the ratio for a Bessel beam. When the period is less than unity, the ratio sharply increases. This jump is not caused by the first side lobe and instead results from another side lobe. The other side lobe becomes lager than the first side lobe in this region, where it becomes the maximum side lobe.

Case 2. In this case, the upper limit of the integral in Eq. (4), $r_{\max}$, is changed to $2.5r_0$ in order to reduce only the first side lobe. Fig. 3(b) shows the relationship between the period and the ratio of the first side lobe to the peak. With parameter values $A_1 = 0.540$, $A_2 = 0.460$, $k_{r1} = 1.243/r_0$, and $k_{r2} = 2.843/r_0$, the first side lobe is reduced to 0.05% of the peak when the period is 0.6.

2.2. Discussion of application to laser drilling

We will now compare SBBs with a Gaussian beam (GB) and with a beam obtained by concentrating a flat beam with a lens (CFB). These two beams are often used in laser drilling. In high aspect ratio laser drilling, there are three important beam characteristics: side lobe intensity, focal depth, and edge sharpness. Side lobes cause damage to the material; focal depth determines the positioning precision required; and edge sharpness affects the tapering of the drilled holes.

Even when – compared with peak intensity – a side lobe is very small, the side lobe can damage the processed material. The extent of the damage depends on both the material and the aspect ratio. While reducing the side lobe to 4.3% (in case 1) may be sufficient to limit damage in some situations, other situations may require greater reduction.

In the former situations (for which the reduction is sufficient), the SBB is most suitable because the SBB has a longer focal depth than either the GB or the CFB, as depicted later in Fig. 11. In addition, the SBB and CFB have a sharper edge than the GB, and the sharpness of these two beams is of the same level, as shown in Fig. 4. Fig. 4 shows beam intensity profiles of the SBB (in case 1) as well as the profiles for the GB and CFB. Each beam has a $1/e^2$ radius of unity. Fig. 4(a) shows complete profiles, while (b) shows partially magnified profiles.

In the latter situations (for which the reduction is insufficient), the SBB in case 2 is applicable. Fig. 5 shows beam intensity profiles of the SBB (in case 2) alongside profiles for the GB and CFB. Although the GB has no side lobe, this beam has a blunter edge than the SBB and CFB. The CFB has an Airy disk intensity profile, and at $r/r_0 = 2$, the side lobe achieves a maximum intensity measuring 1.75% of the peak. The SBB attains maximum side lobe intensity of 10% for the peak at $r/r_0 = 4$. According to Fig. 14, the CFB has a longer focal depth than the SBB, and the SBB has a longer focal depth than the GB. Due to its focal depth and edge sharpness, the GB is less suitable. Henceforth, the CFB and SBB will be compared. Both beams have similar edge sharpness. When the side lobe intensity of the CFB can be neglected, the CFB is preferred to the SBB because the CFB has a longer focal depth. When side lobe intensity cannot be neglected, some protection from side lobe irradiation is necessary because both beams have non-negligible side lobes. Fig. 6 shows a method for avoiding damage caused by side lobe irradiation in which a protection mask is fabricated on the material. Fig. 6(a) and (b) shows applications of this method to laser drilling with the CFB, while (c) shows the application for the SBB. In the cases shown in (a) and (b), the open area of the mask must coincide with the main lobe in order to achieve symmetrical drilling, which requires precise beam positioning in the lateral direction. In addition, for the case shown in (b), the mask must bear main lobe irradiation. In the case shown in (c), precise beam positioning is unnecessary because no side lobe exists near the main lobe.

2.3. Optical system to generate superposed Bessel beam

Fig. 7 shows the theoretical system that generates the SBB. A lens with focal length f is located at $z = 0$. An annular aperture with two slits at $r = r_1$ and r_2 [as illustrated in (b)] is located at $z = -f$. The slit widths are infinitesimal. The SBB is realized at approximately $z = f$.

Let (x_0, y_0) and (x, y) denote the x–y coordinates at $z = -f$ and $z \approx f$, respectively. Consider a plane wave with uniform intensity