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# Bessel beam superposition based on annular reflections

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ABSTRACT

Superposition of a Bessel beam with another beam was usually achieved using an Axicon or a SLM. Here we demonstrate a straightforward but powerful method to superpose a Bessel beam with another Bessel beam or a Gaussian beam based on a Digital Mirror Device (DMD). Different ring or circular patterns could be loaded in the DMD to generate Bessel beams or Gaussian beams respectively. By combining the ring and circular patterns, superposition of a Bessel beam with other Bessel beams or Gaussian beams could be achieved without using beam splitting or other complicated optical setups. The new DMD based Bessel beam superposition method could be easily controlled, quickly switched, or conveniently packed.



Non-diffracting beams have uncommon properties, such as the non-diffraction property over its propagation distance, the self-healing property after an obstacle. A Bessel beam is a well-studied non-diffraction beam that has been successfully applied in many applications, such as improving microscopy resolution [1–3], generate high aspect ratio structures [4–6], moving particles [7–10]. Beam superposition has many applications, for example, a bottom beam could be produced by superposition of two Laguerre–Gaussian modes [11], etc.

Recently, superposition of the non-diffraction Bessel beams attracted more and more attentions. A tractor beam was created by superposition of two or more coaxial Bessel beams using a SLM, which could transport illuminated particles back to its source [12]. Comparing to an optical tweezer or an optical conveyor belt [13], the generated tractor beam could achieve bidirectional movement of particles using one single source. Actually, a Bessel-like beam could be generated by superposing another type of non-diffraction beam—Airy beams [14]. Bessel beam could also be superposed with a Gaussian beam to continuously refuelling an optical filament, which leads to at least one order of magnitude enhancement of natural range [15].

A Bessel beam is usually generated using an annular slit or an Axicon. After fabrication, both the slit and Axicon could not be adjusted conveniently [16]. To increase the flexibility, a Spatial Light Modulation (SLM) has been utilized and programmed to generate Bessel beams [17]. For beam superposition, beam splitting and many other optical elements are always required, i.e., the optical setup is complicated and not easy to be packed. Compared to a SLM, a Digital Micro-mirror Device (DMD) is able to provide a higher damage threshold for powerful laser beam and fast switching rate by reflecting light using a micro-mirror array, which has been successfully generated non-diffraction beams, such as the Bessel beam [18–20]. In the present work, we propose and demonstrate a simple method to generate and superpose a Bessel beam with other Bessel beams or Gaussian beams based on only a DMD without using beam splitting or other complicated setup, which could be easily controlled, quickly switched, conveniently packed, and suitable for powerful laser beam superposition.

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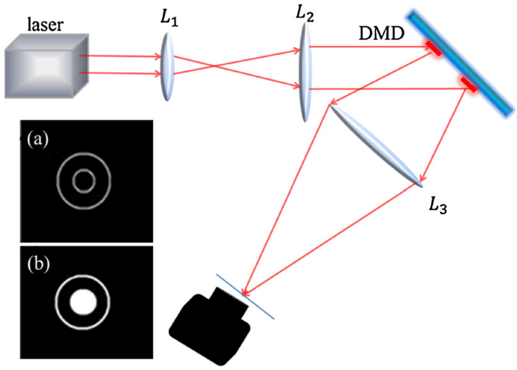


**Fig. 1.** Illustration of the experimental setup for the Bessel beam superposition. Inset (a) the two-ring pattern loaded on a DMD for the superposition of two coaxial Bessel beams; (b) the pattern loaded for the superposition of a Bessel beam and a Gaussian beam.

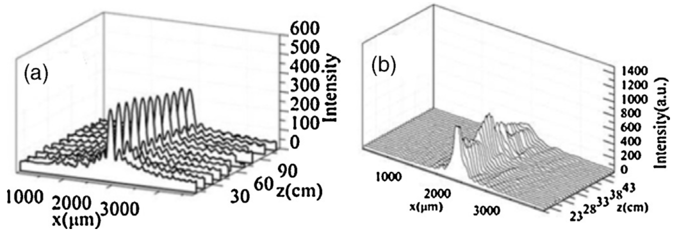


**Fig. 2.** (a) Intensity profile of one Bessel beam along the propagation direction generated using a ring pattern loaded in a DMD; (b) Intensity profile of the superposition of two coaxial Bessel beams along the propagation direction generated using a two-ring pattern loaded in a DMD.

A Bessel beam could be described as

$$\phi(\boldsymbol{x},\boldsymbol{y},\boldsymbol{z};\boldsymbol{k_o}) = \boldsymbol{exp}\left(\boldsymbol{i\beta_o z}\right)\boldsymbol{J}_0\left(\boldsymbol{\alpha_o\rho_o}\right) \tag{1}$$

where, $\boldsymbol{\alpha_o}^2+\boldsymbol{\beta_o}^2=\boldsymbol{k_o}^2, \boldsymbol{x}^2+\boldsymbol{y}^2=\boldsymbol{\rho_o}^2$ , $\boldsymbol{k_o}$ is the wave number and $\boldsymbol{J}_0$ is the zeroth order Bessel function. When $0<\boldsymbol{\alpha_o}<\boldsymbol{k_o}$, the beam intensity distribution is the same as $\boldsymbol{J}_0\left(\boldsymbol{\alpha_o\rho_o}\right)$ in every plane normal to the $z$ axis, i.e., a non-diffracting beam.

When superposing two co-axial Bessel beams [12], the vector potential for the superposed beam of frequency ω and polarization $\hat{\varepsilon}$ could be written in cylindrical coordinates $\mathrm{r}=\left(r,\theta,z\right)$ as

$$\boldsymbol{A}_m(\boldsymbol{r},t)=A_m\{J_m([1-\alpha^2]^{1/2}kr)e^{i\alpha kz}+\eta e^{i\varphi(t)}J_m([1-\beta^2]^{1/2}kr)e^{i\beta kz}\}e^{im\theta}e^{-i\omega t}\hat{\epsilon} \tag{2}$$

where $k=n_m\omega/c$ is the wave number of light in a medium with refractive index $n_m$; $J_m(\cdot)$ is a $m$-order Bessel function of the first kind; $A_m$ is the beam's amplitude. The two beams differ in their axial wavenumbers, $\alpha k$ and $\beta k$, as well as in their relative phase $\phi(t)$.

In the simplified case $m=0$, $\eta=1$, the superposed Bessel beam has axial intensity

$$\lim_{\boldsymbol{r}\to 0}\boldsymbol{I}(\mathbf{r},\boldsymbol{t})=\frac{1}{2}\boldsymbol{cn_m}\varepsilon_0\boldsymbol{\omega}^2\lim_{\boldsymbol{r}\to 0}|\mathbf{A}_0(\boldsymbol{r},\boldsymbol{t})|^2=\boldsymbol{I}_0\boldsymbol{cos}^2\left(\frac{1}{2}\left[\left(\boldsymbol{\alpha}-\boldsymbol{\beta}\right)\boldsymbol{kz}-\boldsymbol{\phi}(\boldsymbol{t})\right]\right) \tag{3}$$

where $\mathrm{I_0}=2\mathrm{A_0^2cn_m}\varepsilon_0\omega^2$. As a result, the beam has evenly spaced intensity maxima at axial positions

$$\boldsymbol{z_j}(\boldsymbol{t})=\left[\boldsymbol{j}+\frac{\varphi(\boldsymbol{t})}{2\boldsymbol{\pi}}\right]\Delta\boldsymbol{z} \tag{4}$$

where $\Delta\mathrm{z}=\lambda/\left(\alpha-\beta\right)$.

The experimental setup is illustrated in Fig. 1, where a DMD (0.7 XGA, Texas Instruments) was loaded with appropriate patterns for beam superposition. A diode laser (1 mW, 635 nm, CPS180, Thorlabs) was used as a monochromatic light source. Two lenses $L_1$ and $L_2$ with focal lengths of 5 cm and 20 cm respectively are used to expand the laser beam diameter to around 1.6 cm in order to match the size of the DMD. The DMD is placed in the focal point of a lens $L_3$ with a focal length of 25 cm. A CMOS camera (DCC1645C, Thorlabs) is used to take image of the superposed beams. More details about the setup to generate Bessel beams could be found in the previous work [20].

A single reflective ring pattern loaded in a DMD could generate a controllable Bessel beam depending on ring diameter and thickness (Fig. 2a) [20]. In order to superpose a Bessel beam with another co-axial Bessel beam, a pattern of two co-axial rings could be loaded in a DMD (Fig. 1 inset a). According to Eq. (4), the superposed laser beam has evenly spaced intensity maxima along the axial direction, which could be measured using the camera moving along the axial direction. When moving the camera from the focal point of lens $L_3$, the intensity of the center of the superposed beam starts to