Generation of controllable nondiffracting beams using multimode optical fibers

X. Zhu,[a)] A. Schülzgen, L. Li, and N. Peyghambarian
College of Optical Sciences, University of Arizona, 1630 E. University Boulevard, Tucson, Arizona 85721, USA

(Received 28 January 2009; accepted 25 April 2009; published online 19 May 2009)

A method of generating nondiffracting beams using multimode optical fibers is reported. When a large-core multimode fiber is spliced onto a piece of single-mode fiber, only linearly polarized ($LP_{0,n}$) modes are excited inside the multimode fiber segment because of mode orthogonality and on-axis excitation. Since the excited $LP_{0,n}$ modes are actually Bessel fields with different transverse wave vectors truncated by the core of the multimode fiber, the beam exiting the multimode fiber facet can form a variety of readily controllable and nearly nondiffracting optical patterns resulting from interference of apertured Bessel fields.
[DOI: 10.1063/1.3138780]

Bessel beams, a special class of nondiffracting beams associated with propagation invariant solutions of the Helmholtz equation, were proposed by Durnin *et al.*[1,2] They have been intensively investigated in the past two decades because of their many applications,[3] e.g., optical driving, particle manipulation, and nonlinear optics. Although it is impossible to experimentally realize an ideal Bessel beam because it would extend over the entire space and contain an infinite amount of energy, a variety of methods to generate approximate Bessel beams have been demonstrated.[2,4–13]

Common techniques for Bessel beam generation apply an annular aperture located at the focal plane of a lens,[2,4] an axicon,[5] an etched hologram, or a computer-generated hologram.[6] Other special methods utilize localized modes[7] or frequency doubling.[8] All of these techniques are based on the fact that a Bessel beam is the result of interference of plane waves propagating on a conic surface. Recently, several techniques differing from this concept have been proposed, such as using an opaque disk[9] or a tunable gradient index of refraction lens.[10] All of these methods involve bulk optics and require careful alignment.

In order to overcome the disadvantage of bulk optical elements and generate Bessel-like beams with compact fiber devices, microaxicons[11] and whispering gallery mode resonators[12] fabricated on facets of optical fibers have been proposed. However, their fabrication is complicated and difficult to control. Recently, Ramachandran and Ghalmi[13] demonstrated a method to generate Bessel-like beams from an optical fiber with a long-period fiber Bragg grating that converts a core mode into a Bessel-like cladding mode. This method, however, is limited to discrete wavelengths.

Here, we present an extremely simple and cost effective method to generate nondiffracting beams using optical fibers. In contrast with all previously demonstrated devices, the beam generated from our fiber device can be easily manipulated, even after the device has been fabricated. Moreover, as a consequence of multimode (MM) interference, the output beam can form a variety of longitudinal intensity shapes that traditionally can only be obtained from interfering Bessel beams with complicated optical systems.[14–16]

[a)]Electronic mail: xszhu@email.arizona.edu.

The design of the fiber device is schematically shown in Fig. 1. A short-piece of large-core MM fiber is spliced onto a conventional single-mode (SM) fiber. Since the performance of this device can be manipulated through the wavelength of the launched light,[17] a single-frequency tunable semiconductor laser was used as the signal source. To measure intensity distributions at various distances from the MM fiber facet, the generated beam was magnified by an aspheric lens with a numerical aperture (NA) of 0.5 and a focal length of 8 mm (Thorlabs, C240TME-C) and the profiles were recorded by an infrared charge coupled device (CCD) camera (Electrophysics, Model 7290 A). Because the aperture of the lens is 8 mm and its NA is much larger than that of the MM fiber (NA=0.2), the effect of lens induced optical aberrations on the reconstruction of the Bessel beams in the CCD camera plane is negligible.

The principle of the fiber device can be described as follows: The fundamental $LP_{0,1}$ mode $[E_{\text{in}}(r,\phi)]$ of the SM fiber is coupled to the MM fiber, where $LP_{0,n}$ modes (n is the radial index) are excited.[17] Mathematically, the fields of the $LP_{0,n}$ modes in the MM fiber core (examples are shown in Fig. 2) are represented by apertured Bessel functions $J_0(k_{z,fn}r)$ with transverse wave vectors $k_{z,fn}=(n_f^2k^2-\beta_{fn}^2)^{1/2}$. Here, $k=2\pi/\lambda$, n_f is the refractive index of the fiber core, β_{fn} are the propagation constants of the $LP_{0,n}$ modes, and r is the radial coordinate and smaller than the core radius of the MM fiber R. Because each $LP_{0,n}$ mode propagates along the waveguide independently with its respective propagation constant, the field at the output facet of the MM fiber is the superposition of Bessel-like fields,

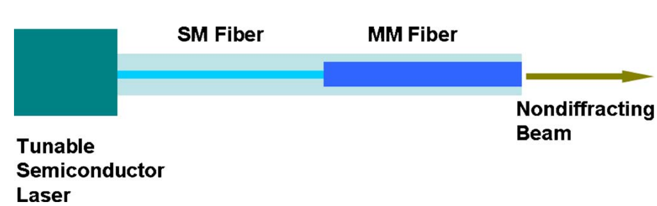

FIG. 1. (Color online) Design of a fiber device generating nondiffracting beams (the figure is not to scale).

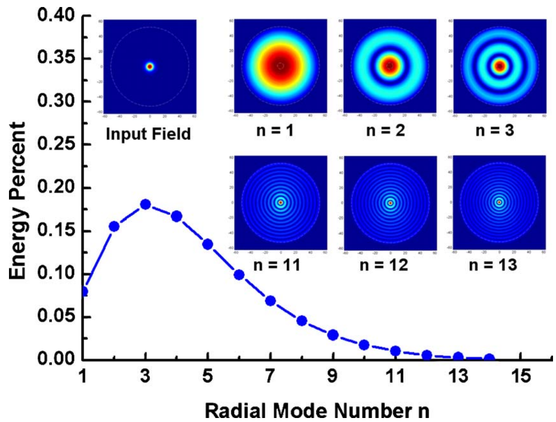

FIG. 2. (Color online) Energy distribution between the excited Bessel-like modes when light from SMF-28 is coupled into the 105 μm core MM fiber. Inset part: calculated profiles of the SM fiber and selected Bessel-like modes inside the MM fiber.

$$E_{\mathrm{out}}(r,L) = \sum_{n=1}^{N} C_n J_0(k_{z,fn} r) e^{i\beta_{fn} L}, \quad r \leq R, \tag{1}$$

where L is the length of the MM fiber segment, N is the number of the excited modes in the MM fiber segment, and C_n are the decomposition coefficient that can be obtained by

$$C_n = \frac{\int\int_S E_{\mathrm{in}}(r,\phi) J_0^*(k_{z,fn} r) ds}{\int\int_S |J_0(k_{z,fn} r)|^2 ds}. \tag{2}$$

Then the beam propagating in free space after leaving the fiber can be approximated as

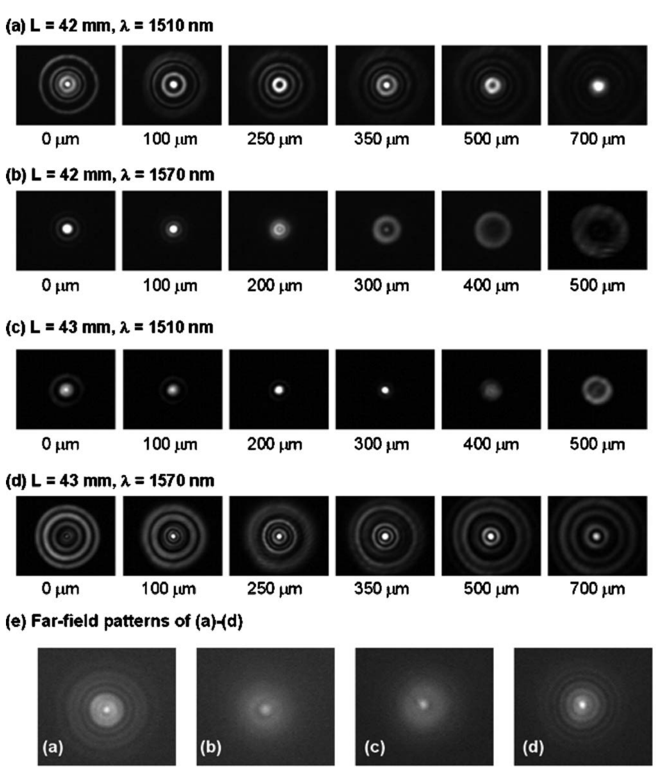

FIG. 3. Beam intensity profiles measured at selected distances from the fiber facet of the MM fiber for wavelengths of 1510 and 1570 nm, respectively, and their corresponding far-field intensity profiles. (a) $L=42$ mm, $\lambda=1510$ nm, (b) $L=42$ mm, $\lambda=1570$ nm, (c) $L=43$ mm, $\lambda=1510$ nm, (d) $L=43$ mm, $\lambda=1570$ nm, and (e) far-field patterns of (a)–(d).

$$E_{fs}(r,z) = \sum_{n=1}^{N} C_n J_0(k_{z,n} r) e^{i(\sqrt{k^2-k_{z,n}^2} z + \beta_{fn} L)}, \tag{3}$$

with $k_{z,n}=k_{z,fn}$. As a consequence of the superposition of multiple Bessel fields, the propagation of the beam can be almost diffraction-free and special beam patterns can be generated at certain axial regions.[14–16] While Eq. (3) is a good approximation for the central propagation-invariant field, the entire field should be obtained from the field $E_{\mathrm{out}}(r,L)$ using diffraction theory.

Because high-order mode fields resemble more closely exact Bessel fields the nondiffracting propagation is most pronounced when higher order $LP_{0,n}$ modes are excited. As an illustration, the intensity profiles of the first three and the last three strongly excited $LP_{0,n}$ modes inside a 105 μm MM fiber are plotted in Fig. 2. The main part of Fig. 2 shows the energy distribution between the excited Bessel-like modes for the case when light from a conventional SM fiber (SMF-28, 8.2 μm core diameter) is coupled into the 105 μm MM fiber. The larger the core diameter of the MM fiber, the more $LP_{0,n}$ modes are excited and the more energy is coupled to high-order $LP_{0,n}$ modes.[17,18] Therefore, a large-core MM fiber is beneficial for nondiffracting propagation. Moreover, because the full width at half maximum (FWHM) of high-order $LP_{0,n}$ modes becomes smaller than that of the input field (compare the first inset and the last three insets in Fig. 2), intensity profiles with extremely small central spot size can be formed, which may find applications in optical interconnection and alignment.

Compared with other devices that usually generate a single Bessel field, whose energy is equally distributed in the central spot and concentric rings, this fiber device can concentrate more energy in the desired nondiffracting pattern (usually the central spot or the first ring) due to controllable MM excitation and interference accomplished by changing the SM-MM fiber core diameter ratio as well as the MM fiber length.[17] Most importantly, due to the wavelength dependence of the interference, the beam exiting the MM fiber can exhibit various longitudinal shapes for different signal wavelengths. Therefore, the nondiffracting pattern generated by this fiber device can be manipulated by solely changing the wavelength.

In Fig. 3 the intensity profiles at selected near-field planes and 10 cm far-field plane are shown for beams generated with two fiber devices. To demonstrate the flexibility and versatility of our approach to generate nondiffracting beams results are shown for two different wavelengths. For the device with a 42 mm long MM fiber segment and an input wavelength of 1510 nm, the pattern near the fiber facet is a very bright central spot that changes to a bright ring after propagating 250 μm. 300 μm from the fiber facet it transforms back to a bright central spot and later changes again into a bright ring at 500 μm. It goes back again to a bright on-axis spot which is then maintained during propagation. Clearly, on-axis intensity oscillations[14,15] as a result of interfering Bessel beams are observed in this case. When the wavelength is 1570 nm, however, the optical field is highly localized ~100 μm from the fiber facet as a consequence of self-imaging of the input field.[16,19] For the fiber device with a 43 mm long MM fiber segment and a wavelength of 1510 nm, again a highly localized optical field occurs at 300 μm. However, when the input wavelength is 1570 nm, the non-

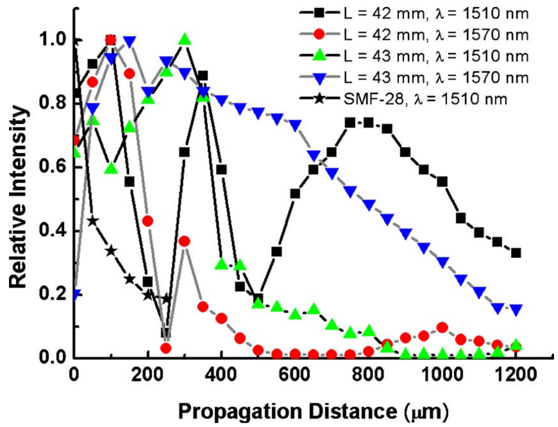

FIG. 4. (Color online) On-axis intensity at the selected distances from the fiber facet of the MM fiber for 1510 and 1570 nm signals, respectively. (On-axis intensity of the beam from SMF-28 is included for comparison).

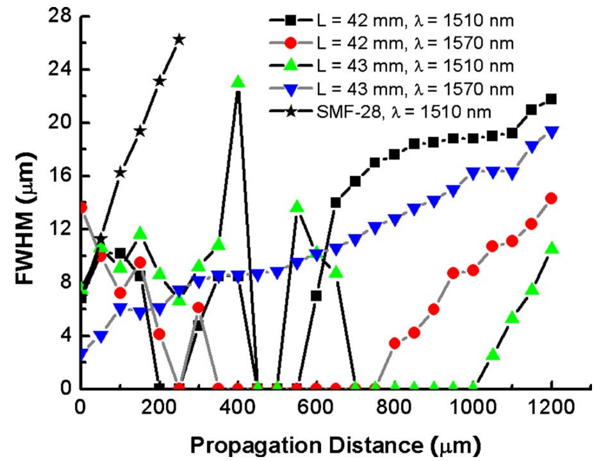

FIG. 5. (Color online) FWHM of the central spot at the selected distances from the fiber facet of the MM fiber for 1510 and 1570 nm signals, respectively. (FWHM of the beam from SMF-28 is included for comparison).

diffracting pattern is always a bright on-axis spot resembling a line trap as a result of constructive addition at the center. Clearly, the beam generated by the fiber device exhibits propagation behavior that depends on the input wavelength and the MM fiber length.

The on-axis intensity at selected distances from the MM fiber facet was obtained from unsaturated CCD images and is plotted in Fig. 4 for each case shown in Fig. 3. For comparison, the intensity evolution of a 1510 nm beam exiting directly from the SM fiber is also shown. For the beam coming from SMF-28, the on-axis intensity reduces to half of its original value after propagating $\sim$50 μm due to diffraction. In contrast, the on-axis intensity of the 1570 nm beam exiting the 43 mm long MM fiber remains above half of its maximum for propagation distances of more than 600 μm, i.e., one order of magnitude longer than without the MM fiber. Oscillations of the on-axis intensity of the 1510 nm beam exiting from the 42 mm long MM fiber show that the fiber device can produce a longitudinal beam shape similar to that of multiple interfering Bessel beams.[14,15] Through a proper choice of signal wavelength and MM fiber length, the fiber device can also realize highly localized optical wave field [cases (b) and (c) in Fig. 3], which are similar to those of fiber lenses.[16,19]

The FWHMs of the central spot of the intensity profiles for the cases shown in Fig. 3 were also obtained from unsaturated CCD images and are plotted in Fig. 5 (Note that the FWHM is assumed to be zero when a bright ring is formed). In contrast with the fast expanding of the beam directly exiting the SM fiber (black stars), beams shaped by the MM fiber segment exhibit nondiffracting propagation. At some positions, the FWHM of the central spot is much smaller than that of the input field due to the survival of high-order $LP_{0,n}$ modes.

In conclusion, a simple and compact fiber device that can generate controllable nondiffracting beams has been demonstrated. Beam profiles generated by this fiber device can be flexibly controlled by the input wavelength as well as the length of the MM fiber segment.

This work is supported by the National Science Foundation through Grant No. 0725479 and the state of Arizona TRIF Photonics Initiative.

[1]J. Durnin, J. Opt. Soc. Am. A **4**, 651 (1987).
[2]J. Durnin, J. J. Miceli, and J. H. Eberly, Phys. Rev. Lett. **58**, 1499 (1987).
[3]D. McGloin and K. Dholakia, Contemp. Phys. **46**, 15 (2005).
[4]C. A. McQueen, J. Arlt, and K. Dholakia, Am. J. Phys. **67**, 912 (1999).
[5]G. Indebetouw, J. Opt. Soc. Am. A **6**, 150 (1989).
[6]A. Vasara, J. Turunen, and A. Friberg, J. Opt. Soc. Am. A **6**, 1748 (1989).
[7]W. B. Williams and J. B. Pendry, J. Opt. Soc. Am. A Opt. Image Sci. Vis. **22**, 992 (2005).
[8]S. Saltiel, W. Krolikowski, D. Neshev, and Y. S. Kivshar, Opt. Express **15**, 4132 (2007).
[9]M. Brunel and S. Coetmellec, J. Opt. Soc. Am. A Opt. Image Sci. Vis. **24**, 3753 (2007).
[10]E. Mcleod, A. B. Hopkins, and C. B. Arnold, Opt. Lett. **31**, 3155 (2006).
[11]S. K. Eah and W. Jhe, Rev. Sci. Instrum. **74**, 4969 (2003).
[12]V. S. Ilchenko, M. Mohageg, A. A. Savchenkov, A. B. Matsko, and L. Maleki, Opt. Express **15**, 5866 (2007).
[13]S. Ramachandran and S. Ghalmi, Proceedings of the Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science, San Jose, 2008 (unpublished), Paper No. CPDB5.
[14]Z. Jaroszewicz, A. Kolodziejczyk, A. Kujawski, and C. Gomez-Reino, Opt. Lett. **21**, 839 (1996).
[15]S. Chavez-Cerda, M. A. Meneses-Nava, and J. M. Hickmann, Opt. Lett. **23**, 1871 (1998).
[16]M. Zamboni-Rached, Opt. Express **12**, 4001 (2004).
[17]X. Zhu, A. Schülzgen, H. Li, L. Li, L. Han, J. V. Moloney, and N. Peyghambarian, Opt. Express **16**, 16632 (2008).
[18]X. Zhu, A. Schülzgen, H. Li, L. Li, Q. Wang, S. Suzuki, V. L. Temyanko, J. V. Moloney, and N. Peyghambarian, Opt. Lett. **33**, 908 (2008).
[19]W. S. Mohammed, A. Mehta, and E. G. Johnson, J. Lightwave Technol. **22**, 469 (2004).