All-fiber optical waveform converter based on deformed catenary nanostructure

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Abstract: We present an optical waveform converter by using a deformed catenary nanostructure at a double cladding fiber end. A vortex beam and Gaussian beam can be generated by wavelength modulation of the helical optical fiber grating fabricated in the double cladding fiber. Through the circular polarization modulation of the deformed catenary nanostructure, the generated beams can realize further various waveform conversions, forming several special beams with unique optical focusing, divergence, and rotation capabilities. Taking advantage of the combination of optical fiber integration and metasurface technologies, the device has broad application prospects in biomedicine, optical communication, optical manipulation, and optical imaging.

1. Introduction

Optical fiber has made great progress in the fields of communication and sensing due to its advantages of low transmission loss, long-distance transmission support, and large communication capacity. Especially, with the emergence of "Lab-on-Fiber" technology, micro-and even nanoscale microstructures can be integrated on one optical fiber, thus realizing miniaturization and integration of all-fiber probes. The all-fiber probe can be used in many fields, from remote measurement in a complex environment (such as human body analysis) to signal processing, drug analysis, and super-resolution imaging [1]. Most traditional optical devices use the difference of refractive index of...
materials to construct a certain spatial structure shape to change the wavefront state \cite{2,3}, and then realize the manipulation of the optical field. In contrast, the "Lab-on-Fiber" technology can accurately manipulate the wavefront phase, polarization state, and environmental parameters through the microstructure on the side \cite{4,5}, fiber end \cite{6,7} or inner \cite{8,9}, so it has the characteristics of small size, flexible structure, dispersion-flattened, low transmission loss and good biocompatibility. Especially in recent years, with the rapid development of metasurface technology \cite{10}, scientists have integrated metasurface on optical fiber. With the mature technology and wide popularization of optical fiber, combined with the unique manipulation of electromagnetic waves by metasurface, it has been endowed with unprecedented optical manipulation ability and enhanced performance, providing a powerful tool for "Lab-on-Fiber" and expanding the practical application of optical metasurface. Such as fiber tweezers \cite{11,12}, biosensing \cite{13,14}, optical imaging \cite{15}, scanning near-field optical microscope \cite{16,17}, etc., with the continuous development of this technology, its performance can be continuously improved and its functions can be continuously enriched, making the "Lab-on-Fiber" go further in the exploration of nanoscale optical control.

As early as the 17th century, catenary was called "the real mathematical and mechanical form" in the architectural field. Because of the characteristic of realizing broadband continuous geometric phase control, catenary has more and more applications in today's optical field. For example, using a single catenary structure unit can realize broadband optical spin Hall effect \cite{18}, achromatic ideal optical angular momentum \cite{1}, planar Bessel beam generator based on metasurface \cite{19}, generate arbitrary near-perfect phase distributions on streamlined metasurface platform \cite{20}, metasurfaces with the ability of continuous wavefront manipulation \cite{21}, a monolayer metasurface with the ability of circular asymmetric transmission and wavefront shaping based on asymmetric spin-orbit interactions \cite{22}, etc. Catenary nanostructures can realize linear and continuous phase control, which makes up for the deficiency of discrete metasurface in phase control. However, the application of optical fiber platform based on catenary nanostructures in vortex beam modulation has not been reported yet.

We present an optical waveform converter by using a deformed catenary nanostructure at a double cladding fiber end. The catenary nanostructures are fabricated in a gold film deposited at the end of the double cladding fiber and prepare a long-period helical optical fiber grating (HFG) in the double-cladding fiber (DCF). On the one hand, the long-period helical optical fiber grating can regulate and control optical waves with different wavelengths to realize the output of the Gaussian beam and vortex beam respectively, and then further modulate the wavefront through a single catenary metal aperture structure to realize the output of different special beams. On the other hand, through changing with circular polarization states of the incident light, the focusing and divergence control of the optical field by a single catenary metal aperture structure can be realized. Therefore,
the device can realize the simultaneous response to wavelength and at the sub-wavelength scale, and realize the wavefront adjustment of different beams.

2. Materials and Methods
As shown in Figure 1a, the all-fiber optical waveform converter with a single catenary metal aperture structure is composed of a double-cladding fiber with long-period helical optical fiber grating in its inner cladding, and a single catenary metal aperture structure is made in the gold film deposited at the end of the double-cladding fiber. According to the light modulation characteristics of the left-handed long-period helical optical fiber grating, at a non-resonance wavelength of $\lambda_1$, the input left-handed polarization light can not be modulated by HFG and maintains guided fundamental mode in the fiber core. However, at a resonance wavelength of $\lambda_2$, the input light can be converted into left-handed vortex mode by HFG and is mainly guided in the inner cladding. And then, by using the single catenary metal aperture structure, the generated fundamental mode or vortex mode can be converted into different special beams. For the incident wavelength with left-handed circularly polarized (LCP) and right-handed circularly polarized (RCP) input light $\lambda_L$ and $\lambda_R$, the vortex beams with LCP and RCP, whose spin angular momentum are respectively $s = +1$ and $s = -1$, can be obtained after being modulated by HFG. Vortex beams with different spin angular momentum can realize the wavefront control of focusing and diverging after exiting from the single catenary metal aperture structure at the fiber end, as shown in Figure 1b.

2.1. Design of catenary aperture
A catenary is a curved shape of a uniform inextensible chain whose two ends are fixed under the action of gravity, which can be expressed as:

$$y = \frac{\Lambda}{\pi} \ln \left( \left\lfloor \sec \left( \frac{\pi x}{\Lambda} \right) \right\rfloor \right),$$

where $\Lambda$ represents the horizontal span of the catenary. According to equation (1), $y$ is infinite at $x = 0.5\Lambda$. Therefore, in our case, the value range of $x$ is limited to the interval $(-0.47\Lambda, 0.47\Lambda)$. The tangential angle $\xi(x)$ of the catenary relative to $x$ is proportional to its position, so the catenary can realize linear and continuous phase control along the curve in the interval $(-\pi, \pi)$, and its expression is:

$$\xi(x) = \tan^{-1} \left( \frac{dy}{dx} \right) = \frac{\pi}{\Lambda} x,$$
Figure 1. Optical field manipulation of double-cladding fiber waveform converter based on the deformed catenary nanostructure. (a) Wavelength modulation. (b) Circular polarization modulation. (c) 2D schematic views of the deformed catenary nanostructure. (d) Phase distribution of the converter under LCP (black) and RCP (red) excitation.

The catenary nanostructure is obtained by translating a single catenary vertically upward and downward. And then, we reverse the left half of the catenary to form a deformed catenary aperture structure, as shown in Figure 1c. It can be expressed as:
\[ y_s = \frac{\Lambda}{\pi} \text{sign}(x) \ln \left( \left| \sec \left( \frac{\pi \Lambda}{\Lambda} \right) \right| \pm \frac{\Delta}{2} \right) . \tag{3} \]

In our case, the horizontal span of the catenary structure is \( \Lambda = 2050 \) nm, and a vertical translation distance is \( \Delta = 200 \) nm (slit width), showing a lightning-like shape. The phase distributions for the cross-polarized light is twice the inclination angle of the aperture along the \( x \) and \( y \) direction can be respectively represented as:

\[
\Phi(x) = \begin{cases} 
-2s\pi x / \Lambda, & x \leq 0 \\
2s\pi x / \Lambda, & x > 0 
\end{cases}, \quad \Phi(y) = \begin{cases} 
2s \arccos(e^{-\pi y / \Lambda}), & y \leq 0 \\
2s \arccos(e^{\pi y / \Lambda}), & y > 0 
\end{cases}. \tag{4}
\]

As shown in Figure 1d, the geometric phase distribution along the \( x \)-axis or \( y \)-axis direction can be obtained by using equation (4). For left-handed circularly polarized light (\( s = +1 \)) excitation, the phase modulation of the catenary aperture is equivalent to a convex lens because the modulation phase of the center of the catenary aperture is larger than the two sides, which has the function of light convergence. On the contrary, for right-handed circularly polarized light (\( s = -1 \)) excitation, the phase modulation of the catenary aperture is equivalent to a concave lens, which has the function of light divergence, because the modulation phase of the catenary aperture is smaller than that of the two sides.

### 2.2 Generation of vortex mode

As shown in Figure 2a-2c, the diameter of the outer cladding, the inner cladding, and the central core of the DCF are \( D_1 = 60 \) \( \mu \)m, \( D_2 = 13 \) \( \mu \)m, and \( D_3 = 4 \) \( \mu \)m, respectively. And their corresponding refractive indices are \( n_1 = 1.4538, n_2 = 1.4555, \) and \( n_3 = 1.4604. \) By using the coupled-mode theory\cite{23}, we analyze the optical modulation characteristics of the single-helix left-handed optical fiber grating (the grating period is 285 \( \mu \)m) of double-cladding fiber to the transmission modes. The output spectra of HFG with a length of 4.9 mm are shown in Figure 2d. We can see that at 808 nm non-resonance wavelength the light guided in DCF is weakly disturbed by the HFG, as shown in Figure 2e. As a result, there is only fundamental core mode output from the HFG, as shown in Figure 2d, f, g. However, from Figure 2d, h, i, and j, we can find that the light can be effectively modulated by the HFG at 775 nm resonance wavelength and completely translates into first-order vortex mode. The coupling relationship between the fundamental mode and vortex mode can be expressed as follows\cite{24}:
Figure 2. Transmission characteristics of helical optical fiber grating of double-cladding fiber. (a), (b) Schematic diagram double-cladding fiber and its optical photograph, respectively. (c) Refractive index distribution of DCF. (d) Output spectra of 4.9 mm length long helical optical fiber grating. (e), (h) Propagation intensity field in HFG at 808 nm non-resonance wavelength and 775 nm resonance wavelength, respectively; (f) and (i) are corresponding to transverse intensity distributions at $z = 4.9$ mm of (e) and (h), respectively. (g) and (j) are corresponding to transverse phase distributions at $z = 4.9$ mm of (e) and (h).

\[
\begin{align*}
\sigma^+ \exp ( +i\phi ) & \quad \text{and} \quad \sigma^- \exp ( +i\phi ) \\
\sigma^+ \exp ( -i\phi ) & \quad \text{and} \quad \sigma^- \exp ( -i\phi )
\end{align*}
\]

where $\sigma^+ = \hat{x} \pm i\hat{y}$, representing left- and right-handed circular polarization, respectively, also denoted by spin angular momentum with $s = \pm 1$. From Equation (5), one can find that the LCP vortex mode $HE_{21}^{even} + iHE_{21}^{odd}$ can be excited by the LCP fundamental mode $HE_{11}^{LCP}$. Similarly, after
exciting the RCP fundamental mode $\text{HE}_{11}^{\text{RCP}}$ with the same resonance wavelength, the RCP vortex mode $\text{TM}_{01} + i \text{TE}_{01}$ can also be obtained.

2.3 Mode excitation and propagation in catenary aperture

As we all know, due to the limitation of the traditional Kirchhoff diffraction theory, even if the aperture thickness is reduced to zero, it cannot be used to analyze the light transmission through a metal aperture structure \cite{25,26}. Therefore, we use the mode expansion and propagation method to analyze the optical propagation of light in the deformed catenary aperture \cite{27,28}. The output field of the deformed catenary aperture can be expressed as:

$$
E = \frac{1}{\pi} \sum_{n=1}^{\infty} \left( b_n + b_n^* \right) E_{n,i} \exp (-j \beta_n h) + \frac{1}{\pi} \sum_{n=1}^{\infty} \left( b_n - b_n^* \right) H_{n,i} \exp (-j \beta_n h) , \quad (6)
$$

where $E_{n,i}$ and $H_{n,i}$ are the $n$-order transverse electric/magnetic mode of the deformed catenary aperture, whose propagation constant is $\beta_n$. And $h = 120 \text{ nm}$ is the thickness of the aperture. $b_n$ and $b_n^*$ are excitation coefficients of forwarding and backward $n$-order mode, respectively, which can be expressed as:

$$
b_n = \frac{\int_{0}^{2\pi} \left( E_{n,i} \times H_{n,i} + E_{n,i} \times H_{n,i}^{(1)} \right) \cdot u_z \, dS}{\int_{0}^{2\pi} \left( E_{n,i} \times H_{n,i} \right) \cdot u_z \, dS} , \quad (7)
$$

2.4 Near-field diffraction

In our case, scalar diffraction theory cannot be used, and the vector diffraction theory should be used to discuss the near-field diffraction of catenary aperture \cite{29}. Based on the vector diffraction theory of vector Rayleigh-Somme diffraction-free integral formula, the electric field at any point $P_1(x_1, y_1, z_1)$ outside the catenary aperture ($z = 0$) can be obtained by the following method:

$$
\vec{E}(P_1) = \frac{k z_1}{2\pi} \int_{0}^{2\pi} \int_{0}^{\infty} \frac{e^{ik \rho}}{\rho^2} \left( 1 - \frac{1}{ik \rho} \right) dx_0 dy_0' , \quad (8)
$$

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where \( \rho = \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2 + z_i^2} \). \( E_{z=0} \) is the vector electric field output by the catenary aperture at the fiber end, which lies in the \( z = 0 \) plane. Equation (8) is a complete Rayleigh-Sommerfeld solution, which can accurately describe the propagation of light field from the end of optical fiber in free space.

3. Results

As mentioned above, the fundamental mode and the vortex mode can be generated by wavelength modulation of HFG in DCF. For the convenience of description, we define a new uvz Cartesian coordinate system that rotates 30° counter-clockwise around the origin of x-y plane, as shown in Figure 3a. While the guided mode of DCF is coupled into the catenary aperture, from Equation (6), we can deduce that plenty of catenary aperture modes can be excited. However, the higher order of the catenary aperture mode is, the greater loss it has. Therefore, only the low order modes can be output from the catenary aperture, while other modes almost lose. From Equation (4), we can also find that inverse linear phase modulation can be realized by the deformed catenary aperture for LCP and RCP exciting light. Therefore, to realize waveform conversion, different output fields can be formed while different circular polarization guided modes of DCF pass through the catenary aperture, as shown in Figures 3a-3d. For LCP fundamental mode (\( s = +1 \)) illumination, when the slit width \( \Delta \) is less than or equal to 200 nm, the intensity distribution of the catenary aperture output field expands to both sides along the \( u \) direction, as shown in Figure 3a. On the contrary, if \( \Delta \) is more than 200 nm, the output field distribution tends to be concentrated. However, compared with LCP fundamental mode, the small catenary aperture (\( \Delta \leq 200 \text{ nm} \)) excited by RCP fundamental mode (\( s = -1 \)) can produce a concentrated field in the aperture center, while a relatively dispersed field can be formed for the large aperture (\( \Delta > 200 \text{ nm} \)), as shown in Figure 3b. Figures 3c and 3d give the output field distributions of the catenary aperture in the excitation of LCP and RCP vortex modes, respectively. The vortex beam has a dark center and is distributed in a hollow shape. Therefore, unlike the fundamental mode excitation, we can see that there is no energy distribution at the center of output fields from the aperture. When the width of the aperture \( \Delta \) is less than or equal to 200 nm, most of the energy is distributed at both ends of the aperture. However, for the larger aperture (\( \Delta > 200 \text{ nm} \)), the output field excited by vortex mode has similar distribution characteristics with that excited by fundamental mode.

Whether the fundamental mode excitation or vortex mode excitation, the catenary aperture can not remain a single-mode transmission along \( v \) direction when the width of the aperture \( \Delta \) is large enough, such as 250 nm and 300 nm. We can find that there are two or even more extreme points of the output intensity field along the \( v \) direction, showing a multimode transmission, as shown in the...
last two rows of Figures 3a-3d. Therefore, the proposed optical waveform converter based on deformed catenary aperture can achieve both wavelength and circular polarization modulation.

**Figure 3.** Calculational results of the output intensity fields from the catenary aperture with different input modes and slit width $\Delta$. (a), (b) LCP and RCP fundamental modes at 808 nm, respectively. (c), (d) LCP and RCP vortex modes at 775 nm, respectively.
We define the polarization conversion efficiency (PCE) as:

\[
PCE = \frac{t_{uu}^2}{t_{uu}^2 + t_{uv}^2},
\]

(9)

Where \( t_{uu} \) and \( t_{uv} \) are the corresponding to co- and cross-polarized transmissions of the \( u \)- and \( v \)-direction. As shown in Figure 4, with the excitation of vortex mode, PCE increases linearly within aperture widths 100 to 200 nm, and PCE is stable at 60% within aperture widths larger than 200 nm. PCE presents the trend of consecutive increasing within aperture widths 100 to 200 nm and rapidly growth within aperture widths larger than 200 nm when the excitation of the fundamental mode. The average value for vortex mode excitation and fundamental mode excitation are 60.2% and 72.1%, respectively. In a word, when the aperture width is larger than 200 nm, the catenary aperture keeps multimode transmission along the \( v \) direction. Therefore, the PCE is rapidly increased. However, whether excited by fundamental mode or vortex mode, the PCE of a single catenary aperture is low. And PCE can be significantly improved by using a catenary aperture array.

To further analyze waveform conversion characteristics, by using vector diffraction theory (see Equation (8)), we calculate the propagation fields of light beams generated by fundamental modes and vortex modes excited catenary aperture in free space, as shown in Figures 5 and 6, respectively. Because of the different linear phase modulations of LCP and RCP light by the deformed catenary aperture (see Equation (4)), just like a lens, the focusing and diverging output fields can be obtained, as shown in Figures 5a and 5d, respectively. However, whether LCP light excitation or RCP light excitation, the energy distributions of transverse fields are almost extending along \( v \) direction and compressing along \( u \) direction, as shown in Figures 5b and 5e. The reason is that the diffraction...
effect along the deformed catenary aperture direction ($u$ direction) is much stronger than its vertical direction ($v$ direction). We also give the simulation results based on the finite-difference time-domain (FDTD) method, as shown in the left columns of Figures 5b and 5e. We can find the calculation results are agreed with the simulation results. However, the latter always shows a stronger diffraction effect than the former due to the limitation of simulation precision. Particularly, the transverse fields can rotate counterclockwise around the origin to increase the transmission distance. This is a remarkable characteristic to realize an optical rotating field by using a deformed catenary aperture. It can be inferred that if we fold the deformed catenary aperture along with the $y$-axis, the output transmission field will rotate clockwise.

**Figure 5.** Transmission characteristics of output fields generated by the proposed waveform converter excited by fundamental modes at 808 nm wavelength. (a), (b) The longitudinal ($uoz$ plane) and transverse distribution of transmission intensity fields for a 200 nm width catenary aperture. (c) FDHM curves of the longitudinal transmission intensity fields in $uoz$ plane for
different width catenary apertures. (a)-(c) and (d)-(f) are corresponding to LCP and RCP fundamental mode excitation, respectively.

Figures 5c and 5f show the calculation results of the full-width half maximum (FDHM) of output transmission fields with different widths of deformed catenary apertures changing with an increase of transmission distance. In the range of several hundred nanometers, when \( \Delta = 100 \text{ nm}, 150 \text{ nm}, 200 \text{ nm} \), the FDHM of transmission fields of the catenary apertures excited by LCP light decreases sharply along \( u \) direction, as shown in Figures 5c. Therefore, the transmission fields show a strong convergence. For RCP light excitation, when \( \Delta = 250 \text{ nm}, 300 \text{ nm} \), a similar phenomenon can be observed in Figure 5f. The reason is that the energy distribution of the output beam from the catenary aperture always expands to both sides, as shown in Figures 3a and 3b, so it is easy to form focusing on the optical axis. For LCP light excitation, when \( \Delta = 250 \text{ nm}, 300 \text{ nm} \), the FDHM of the transmission field can always increase along \( u \) direction, which indicates that the light no longer converges, but directly diverges, as shown in Figure 5c. For RCP light excitation, we can also obtain similar results when \( \Delta = 100 \text{ nm}, 150 \text{ nm}, 200 \text{ nm} \), as shown in Figure 5f. Therefore, a concentrated field (see Figures 3a and 3b) generated by the deformed catenary aperture can be transmitted divergently in free space. Compared with Figures 5c and 5f, we can find that the FDHM excited by LCP light is much less than that by RCP light due to circular polarization modulation of deformed catenary aperture. For a catenary aperture with \( \Delta = 200 \text{ nm} \) excited by LCP fundamental mode, the strongest focusing effect and the smallest FDHM can be obtained at \( z = 500 \text{ nm} \).

Remarkably, we can break the diffraction limit in this way. Different from fundamental mode excitation, the propagation fields excited by LCP and RCP vortex modes always exist a dark center due to their carrying orbital angular momentum and show the faster decrease of optical intensity as increasing transmission distance, as shown in Figures 6a and 6d. Except for the background noise caused by incomplete polarization conversion, the FDTD simulation results are very consistent with the theoretical results, as shown in Figures 6b and 6e. Because of the hollow distribution of the vortex beam, only the two ends of the deformed catenary aperture can achieve effective modulation. Most of the energy of the output field of the deformed catenary aperture excited by vortex beams is diffused to both ends of the aperture (see Figures 3c and 3d). Therefore, whether LCP excitation or RCP excitation, the phenomenon of the transverse fields rotating counter-clockwise around the origin is not obvious, as shown in Figures 6b and 6e, which indicates that light modulation of the central zone of the deformed catenary aperture plays a key role in output field spinning. However, compared with Figures 5c, 5f, 6c, and 6f, we can find that there is always a stronger focusing effect along the \( u \) direction and a similar diverging effect.
along the $v$ direction. Within a few hundred nanometers, the FDHM of the transmission fields excited by LCP and RCP vortex modes decreases faster than that excited by fundamental modes. The focusing effect can limit the circular polarization modulation. Therefore, the field divergence caused by the polarization modulation of RCP light is not obvious, as shown in Figure 6f. Compared with LCP vortex beam excitation, the transmission fields excited by the RCP vortex beam have an extra diffraction area marked in Figure 6f. In the diffraction area, the focusing effect will be neutralized by polarization modulation. Similarly, for a catenary aperture with $\Delta = 200$ nm excited by LCP vortex mode, the strongest focusing effect can be achieved at $z = 500$ nm, as shown in Figure 6c. However, compared with fundamental mode excitation, the difference is that, due to the unique field distribution of output beam in the penultimate row of Figure 3d, the smallest FDHM can be obtained at $z = 350$ nm for a catenary aperture with $\Delta = 250$ nm excited by RCP vortex mode, as shown in Figure 6f.
**Figure 6.** Transmission characteristics of output fields generated by the proposed waveform converter excited by vortex modes at 775 nm wavelength. (a), (b) The longitudinal (uo\(z\) plane) and transverse distribution of transmission intensity fields for a 200 nm width catenary aperture. (c) FWHM curves of the longitudinal transmission intensity fields in uoz plane for different width catenary apertures. (a)-(c) and (d)-(f) are corresponding to LCP and RCP vortex mode excitation, respectively.

**4. Conclusions**

The combination of optical fiber integration and metasurface technologies can bring an unprecedented degree of freedom to optical operation at the nanometer scale. In this work, by integrating one-dimensional long helical fiber grating and two-dimensional deformed catenary nanostructures, the proposed all-fiber waveform converter can not only control wavelength modulation but also realize the circular polarization modulation. The fundamental mode and vortex mode guided by DCF can be generated by HFG wavelength modulation. And different responses of LCP and RCP modes also can be obtained by circular polarization modulation of the deformed catenary nanostructure. The coupled-mode theory, mode expansion and propagation method, and vector diffraction theory are used to study the light propagating in HFC, deformed catenary aperture, and free space respectively. The calculation results show that the device can realize a variety of beam conversions, and the generated beams have unique optical focusing, divergence, and rotation capabilities. This device has these unique electromagnetic characteristics of the optical fiber and metasurface, which can make the generated beam break through the diffraction limit, and broadens the potential functions and application prospects of "Lab-on-Fiber".

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Designing an all-fiber waveform converter by integrating one-dimensional long helical fiber grating and two-dimensional deformed catenary nanostructure. Through wavelength and circular polarization modulation, the device has unique ability in optical focusing, divergence and rotation, which can make the generated light beam break through the diffraction limit. It has potential applications in optical manipulation and imaging.