

# PHOTONICS Research

## High-purity orbital angular momentum mode combs via a helical sampled fiber Bragg grating

RUI LIU,<sup>1,2</sup>  ZHIYONG BAI,<sup>1,2,\*</sup>  CAILIANG LV,<sup>1,2</sup> JIANJUN RAN,<sup>1,2</sup> JIA HE,<sup>1,2</sup> SHIQIN QIN,<sup>1,2</sup> ZHIWEI LIN,<sup>1,2</sup> XIZHEN XU,<sup>1,2</sup>  YIPING WANG,<sup>1,2</sup>  AND JUN HE<sup>1,2</sup> 

<sup>1</sup>State Key Laboratory of Radio Frequency Heterogeneous Integration, Key Laboratory of Optoelectronic Devices and Systems of Ministry of Education/Guangdong Province, College of Physics and Optoelectronic Engineering, Shenzhen University, Shenzhen 518060, China

<sup>2</sup>Shenzhen Key Laboratory of Photonic Devices and Sensing Systems for Internet of Things, Guangdong and Hong Kong Joint Research Centre for Optical Fibre Sensors, Shenzhen University, Shenzhen 518060, China

\*Corresponding author: baizhiyong@szu.edu.cn

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Orbital angular momentum (OAM) mode combs offer a promising path to high-capacity optical communication, yet their practical development is hindered by challenges at both system and component levels. While existing platforms like integrated microring resonators and spatial light modulators struggle with inherent issues of high insertion loss, poor fiber compatibility, and limited flexibility, the fiber-compatible alternative—conventional fiber Bragg gratings (FBGs)—is itself constrained by a severe channel bottleneck, typically generating only a single OAM mode. To concurrently address these system-level incompatibility and component-level capacity limitations, we propose a novel OAM comb generator based on a helical-sampled FBG (HS-FBG) inscribed on a ring-core fiber. The helical sampling function introduces a spiral phase front, and the coupling process is governed by the angular momentum conservation law, which creates a deterministic mapping between the sampling order and the topological charge of the OAM mode. This enables the simultaneous excitation of multiple high-purity OAM modes (specifically, from the  $-3$ rd to the  $+3$ rd order) directly within the fiber medium. Experimental results demonstrate that the fabricated device generates a clean OAM mode comb, with the purity of each order exceeding 95%. This work overcomes the channel-number bottleneck of fiber-grating-based generators while fully leveraging their inherent advantages of low loss and seamless fiber integration, presenting a robust solution for high-dimensional multiplexing. © 2026 Chinese Laser Press

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### 1. INTRODUCTION

Orbital angular momentum (OAM) [1–4], as a fundamental physical dimension of light, theoretically has an infinite number of modes that are mutually orthogonal, providing a revolutionary new dimension for breaking through the communication capacity bottleneck. Its unique helical phase wavefront characteristics enable OAM to not only show great potential in optical micromanipulation [5–9], super-resolution microscopy [10–12], quantum information processing [13–18], and other fields [19–22], but also play a key role in space-division multiplexing technology [23–27], paving the way to significantly enhance the channel capacity and spectral efficiency of optical communication systems.

Techniques for generating OAM have developed into various schemes, including passive methods such as digital holography based on spatial light modulators (SLMs) [28–31], geometric phase modulation using q-plates [10,32,33], wavefront shaping with spiral phase plates [34–37], and

nanostructure control with metasurfaces [38–40], as well as active methods such as direct emission from semiconductor lasers [41–44]. These techniques can efficiently generate single OAM modes but are limited to single-channel output, unable to support multimode parallelism, which restricts further enhancement of optical communication capacity. To overcome this bottleneck, the concept of OAM combs was proposed, the core of which is to simultaneously generate multiple OAM modes with different topological charges using a single device, achieving mode-domain multiplexing to exponentially increase channel capacity [45–53]. Existing OAM comb generation schemes mainly fall into three categories: integrated optical platforms such as Kerr nonlinear vortex microcombs in microring resonators [45–47], which can generate multiple orders of OAM but are limited by high scattering loss and complex nanofabrication; free-space schemes such as multi-channel coding via metasurface holography [50] and diffractive optical design with SLMs [49,53], which offer high flexibility

but suffer from insertion losses and poor compatibility with fiber systems; and electro-optic modulation techniques [48], which allow dynamic reconfiguration but are difficult to implement in practice due to limited bandwidth and low efficiency. The common critical drawbacks of these methods are high loss (with mode purity generally below 90%), lack of fiber compatibility, and insufficient stability, making them unable to meet the low-power and integrated requirements of modern communication systems. It is noteworthy that the fiber grating scheme [54–60], with its inherent low loss (<0.5 dB) and fiber compatibility advantages, is regarded as a potential solution. However, traditional fiber gratings based on uniform or tilted grating structures can only generate a single OAM mode [60] or require complex cascades to achieve a limited output [57], resulting in restricted channel capacity and increased crosstalk. Helical gratings can produce multiple channel OAMs, but precise phase matching cannot be achieved simultaneously across different channels, and the mode quality is uneven [59].

In response to the aforementioned challenges, this paper proposes and experimentally validates a novel OAM mode comb generator based on a helical-sampled fiber Bragg grating (HS-FBG). The proposed HS-FBG device is fabricated within a ring-core fiber using femtosecond laser direct writing technology. Based on the conservation of angular momentum, a helical sampling structure is designed to achieve precise binding between OAM orders and sampling levels. This enables efficient conversion of the incident fundamental mode (LP<sub>01</sub>) into a series of OAM modes with specific topological charges, thereby directly generating an OAM comb within the fiber. Experimental results demonstrate that the fabricated OAM comb can directly generate -3rd-, -2nd-, -1st-, 1st-, 2nd-, and 3rd-order OAM modes, with purity exceeding 95% for all generated modes, ensuring high-quality signal transmission.

## 2. PRINCIPLE AND DESIGN OF THE HS-FBG

The physical essence of the HS-FBG lies in the synergistic control of optical wave modes and orbital angular momentum through the introduction of periodic refractive index modulation along the fiber axis ( $z$ ) and angular direction ( $\phi$ ). Its refractive index modulation function can be expressed as

$$\delta_n(z, \phi) = \sigma(z, \phi) \cdot \Delta n_{ac} \cdot \cos\left(\frac{2\pi}{\Lambda_g} z\right). \quad (1)$$

Among these,  $\Lambda_g$  is the grating period, determining the fundamental wavelength for Bragg reflection;  $\Delta n_{ac}$  is the refractive index modulation depth; and  $\sigma(z, \phi)$  is the helical sampling function, exhibiting both axial periodicity  $\Lambda_s$  (sampling period) and angular periodicity. The helical sampling function is given by

$$\sigma(z, \phi) = \sum_{m=-\infty}^{\infty} c_m \exp\left[im\left(-\frac{2\pi}{\Lambda_s} z + l_s \phi\right)\right]. \quad (2)$$

Here,  $m$  is the sampling order (integer),  $c_m$  represents the Fourier coefficient, and  $l_s$  is the helical topological charge, which denotes the number of  $2\pi$  rotations of the helix per

sampling period  $\Lambda_s$ ; its sign indicates the handedness (positive for right-handed). It is important to distinguish  $l_s$  from the OAM topological charge  $l$  of the output beam:  $l_s$  sets the step size for angular momentum conservation [see Eq. (7)].

Substituting Eq. (2) into Eq. (1) and expanding the cosine term into two complex exponentials, we obtain

$$\begin{aligned} \frac{\Delta n_{ac}}{2} \sum_m c_m \left\{ \exp\left[i\left(\frac{2\pi}{\Lambda_g} - m\frac{2\pi}{\Lambda_s}\right)z + iml_s\phi\right] \right. \\ \left. + \exp\left[i\left(-\frac{2\pi}{\Lambda_g} - m\frac{2\pi}{\Lambda_s}\right)z + iml_s\phi\right] \right\} + \text{c.c.} \end{aligned} \quad (3)$$

In this work, the grating is designed for second-order Bragg resonance ( $q = 2$ ). Therefore, the effective axial wave vector for the backward reflection is twice the fundamental grating wave vector, i.e.,  $4\pi/\Lambda_g$ . Only the first exponential term satisfies the phase-matching condition for backward reflection (the second term corresponds to a non-phase-matched process). Retaining this term and absorbing the constant factors into the coupling coefficient  $\kappa_m$ , we obtain the effective index modulation for each sampling order  $m$ :

$$\delta_n(z, \phi) = \sum_m \kappa_m \exp\left[i\left(\frac{4\pi}{\Lambda_g} - m\frac{2\pi}{\Lambda_s}\right)z + iml_s\phi\right] + \text{c.c.} \quad (4)$$

Each one represents an independent coupling channel. Axial wave vector component  $4\pi/\Lambda_g - m \cdot 2\pi/\Lambda_s$  determines the wavelength position of the  $m$ th-order resonance peak; angular phase component  $ml_s\phi$  determines the OAM mode generated by the coupling of this channel.

This structure not only endows the grating with spiral phase but also introduces angular momentum selectivity. Based on coupled-mode theory [61], efficient energy coupling from the incident mode (typically the fundamental mode LP<sub>01</sub>, propagation constant  $\beta_{in}$ , OAM order  $l_{in} = 0$ ) to the target mode ( $\beta_{out}$ ,  $l_{out}$ ) requires two conditions to be satisfied simultaneously. First, the propagation constant matching (conservation of axial momentum) must be satisfied. From the exponential in  $z$  in Eq. (4), the phase-matched term requires

$$\beta_{out} + \beta_{in} = \frac{4\pi}{\Lambda_g} - m\frac{2\pi}{\Lambda_s}. \quad (5)$$

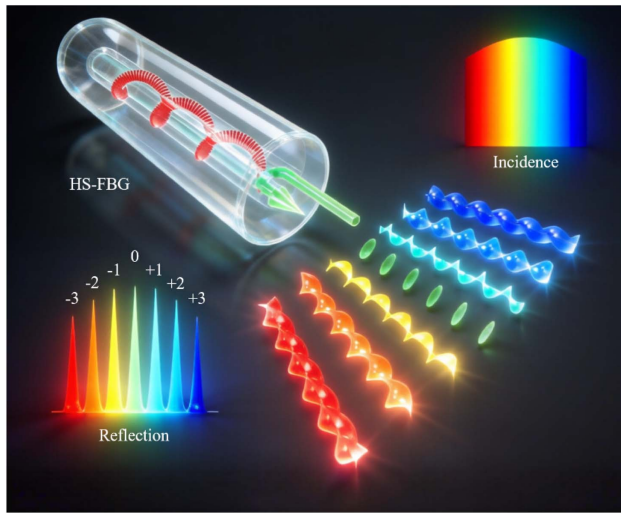
Substituting  $\beta = 2\pi n_{eff}/\lambda$  into Eq. (5), the resonance wavelength for the  $m$ th-order channel is

$$\lambda_m = \frac{n_{eff}^{out} + n_{eff}^{in}}{\frac{2}{\Lambda_s} - \frac{m}{\Lambda_g}}. \quad (6)$$

The minus sign in the denominator arises from the helical writing direction.

Simultaneously, the requirement that the angular integral in the coupling coefficient must be non-zero to satisfy angular momentum matching (conservation of angular momentum) must be met:

$$l_{out} - l_{in} = ml_s. \quad (7)$$



**Fig. 1.** Schematic diagram of the HS-FBG and its working principle.

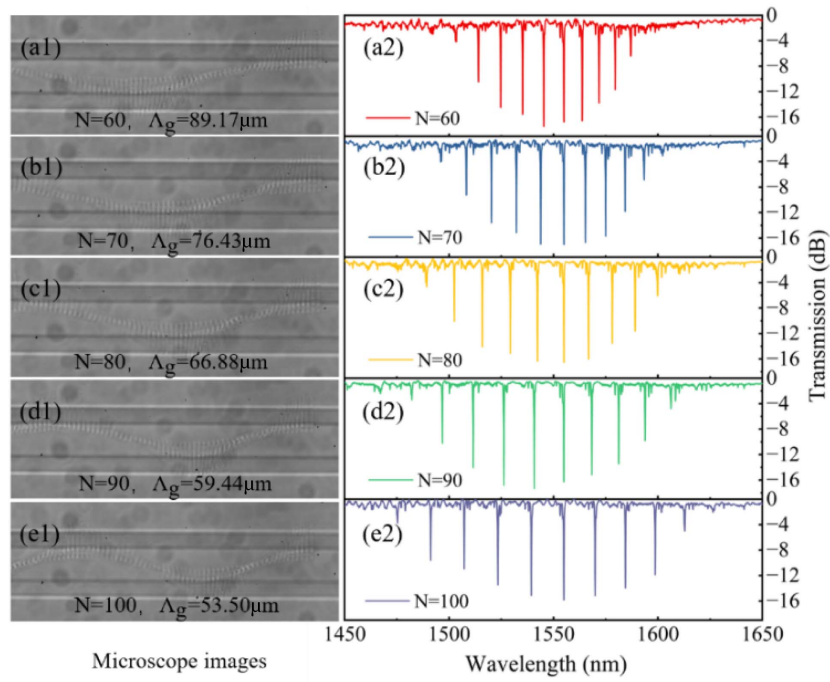
That is, effective coupling occurs only when the orbital angular momentum topological charge of the input and output modes satisfies the condition. When  $l_{\text{in}} = 0$ , the OAM order of the  $m$ th-order resonant wavelength output mode is  $l_{\text{out}} = ml_s$ . For our device with  $l_s = 1$ , we, therefore, obtain  $l_{\text{out}} = m$ . This establishes a deterministic mapping between the sampling order  $m$  and the topological charge of the generated OAM mode. A complete derivation of Eqs. (1)–(7) including the sign conventions and the treatment of the second-order Bragg grating is provided in Appendix A.

The HS-FBG structure is shown in Fig. 1. We selected a ring-core fiber with an inner cladding radius of  $3.5 \mu\text{m}$ , annular core width of  $4 \mu\text{m}$ , and outer cladding radius of  $62.5 \mu\text{m}$ , which supports long-distance transmission of OAM modes within  $\pm 3$  orders. Within the core region of the ring-core fiber, a structure featuring three-dimensional helical periodic refractive index modulation was successfully fabricated using femto-second laser direct writing technology. Its most distinctive structural feature is that the grating fringes are not arranged in a straight line along the fiber axis. Instead, as indicated by the red spiral line, they advance in a helical pattern with a specific pitch and topological charge, thereby forming a complex diffraction unit within the fiber that combines both axial and angular periodicity. When a broadband light beam is incident from one end of the grating, this spiral grating simultaneously performs two key functions. First, its helical sampling structure excites equidistant discrete reflection peaks across the spectral domain, forming a comb-like spectrum as shown in the lower left corner of the figure. This achieves channel selection of the incident broadband light in the wavelength dimension. Second, its intrinsic helical phase modulation directly converts light from different reflection channels (corresponding to diffraction orders labeled  $-3$  to  $+3$  in the figure) into orbital angular momentum modes carrying the respective topological charges. This naturally generates multiple vortex beams with distinct wavelengths and orders at the output, enabling parallel manipulation and output of both wavelength and spatial mode degrees of freedom.

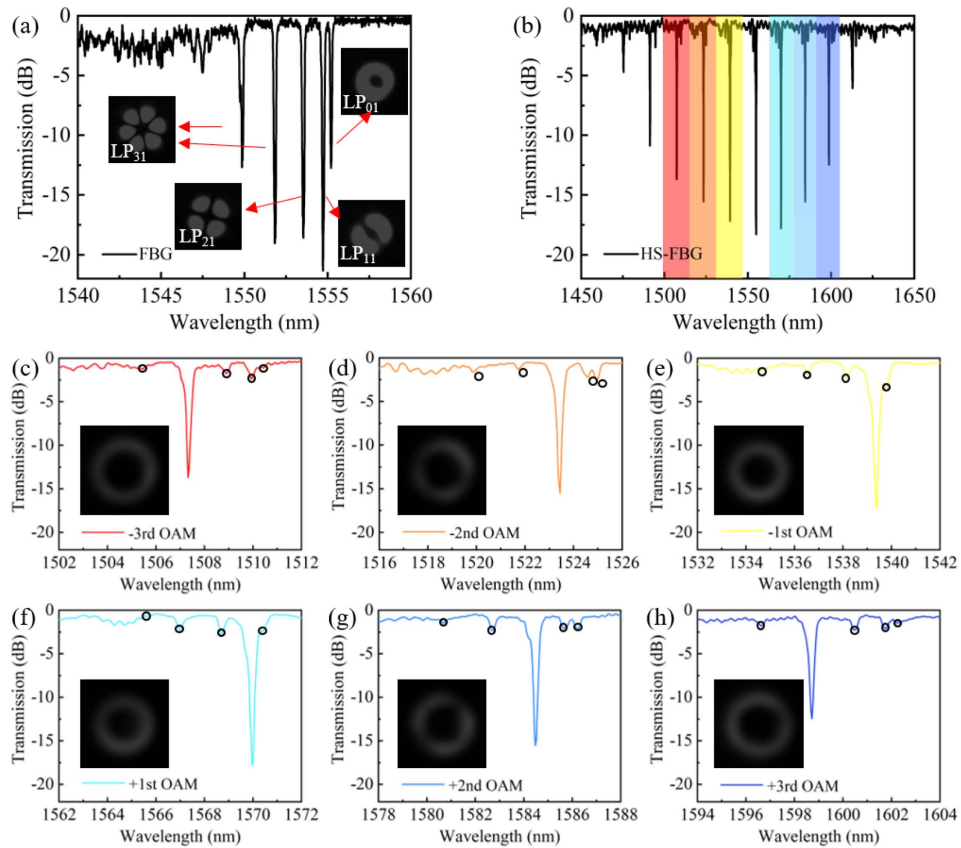
### 3. EXPERIMENTAL RESULTS

A systematic investigation into the regulation mechanism of spiral sampling periods was conducted by designing and fabricating a series of HS-FBGs with varying parameters. All samples were based on the same second-order Bragg design, with a fixed grating period of  $\Lambda_g = 1.07 \mu\text{m}$  and a fixed total grating length of  $L = 5.35 \text{ mm}$ . By varying the helical sampling period, the total grating length was divided into  $N = 60, 70, 80, 90$ , and  $100$  sampling periods, corresponding to sampling periods  $\Lambda_s = L/N$  of  $89.17, 76.43, 66.88, 59.44$ , and  $53.50 \mu\text{m}$ , respectively. The experimental results are summarized in Fig. 2. The left-column micrographs [Figs. 2(a1)–2(f1)] provide direct visual evidence of the successfully inscribed helical structures, showing well-defined and consistent grating fringes with distinct periodicities that correspond to the designed  $\Lambda_s$ . The corresponding transmission spectra [Figs. 2(a2)–2(f2)] on the right comprehensively demonstrate the comb-like filtering response. A key observation is the systematic increase in spectral dip spacing ( $\Delta\lambda$ ) as  $\Lambda_s$  decreases (or equivalently, as  $N$  increases), with the widest channel spacing achieved at the smallest  $\Lambda_s$  of  $53.50 \mu\text{m}$  ( $N = 100$ ). The device with  $N = 100$  was selected for the final demonstration because it provides the largest channel spacing, ensuring clear spectral separation of the OAM comb channels while maintaining sufficient reflection efficiency across all orders. This series of spectral responses visually validates the theoretical relationship  $\lambda_m \propto 1/(2/\Lambda_g - m/\Lambda_s)$ , demonstrating that the channel spacing in the comb spectrum can be effectively and predictably customized by precisely designing  $\Lambda_s$ . To quantitatively verify this relationship, we compared the measured adjacent channel spacings for the  $N = 100$  device with the theoretical values calculated from the corrected Eq. (5) using wavelength-dependent effective indices obtained from finite-element simulations. As shown in Table 2 in Appendix A, the experimental spacings agree with the theoretical ones to within 2.1% across all six adjacent channel pairs, well within the experimental uncertainty (spectral resolution  $0.1 \text{ nm}$  and slight variations in effective indices). This confirms the validity of the theoretical model. These findings provide crucial experimental evidence for the parallel multi-wavelength orbital angular momentum modulation capability of the HS-FBG.

For the purpose of validating the core physical mechanism, a systematic comparison is presented between the spectral characteristics of HS-FBGs and conventional FBGs etched line-by-line. Specific results are shown in Fig. 3. Figure 3(a) displays the transmission spectrum of the conventional grating, revealing five discrete resonance dips. Mode field analysis confirms that these dips correspond sequentially to the fundamental mode  $\text{LP}_{01}$  and the reverse coupling of higher-order modes  $\text{LP}_{11}$ ,  $\text{LP}_{21}$ , and  $\text{LP}_{31}$  from longer to shorter wavelengths. Notably, the additional resonance dip at the shortest wavelength originates from coupling channels between higher-order modes, as verified by simulations. Figure 3(b) presents the transmission spectrum of a helical sampling grating, whose most prominent feature is the periodic comb-filtering response introduced by the sampling structure. Within the wavelength channels corresponding to specific diffraction orders (comb teeth), the spectral zoomed-in areas of Figs. 3(c)–3(h) reveal



**Fig. 2.** (a1)–(e1) Microscopic images and (a2)–(e2) transmission spectra of spiral-wound fiber Bragg gratings under different sampling periods ( $N = 60, 70, 80, 90, 100$ ).



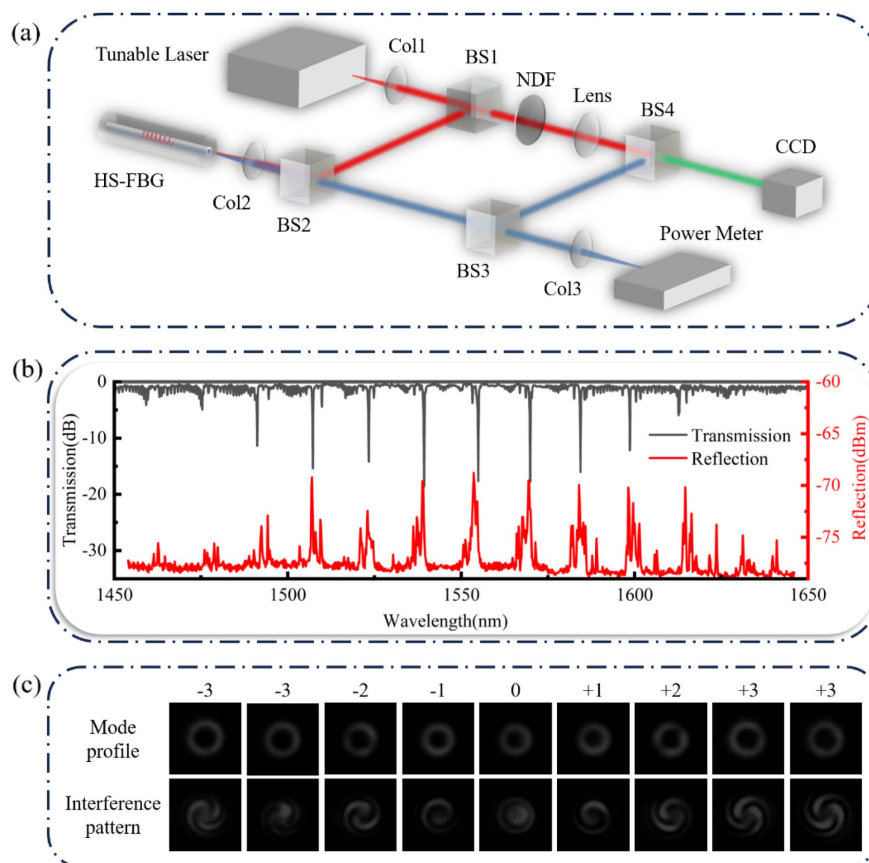
**Fig. 3.** HS-FBG enables parallel modulation and purification of wavelength-orbital angular momentum. (a) Reference spectrum of a conventional FBG; (b) comb-like transmission spectrum of the HS-FBG, enabling wavelength channelization; (c)–(h) selective mode coupling in each channel, exciting only pure OAM modes with specific topological charges ( $l = \pm 1, \pm 2, \pm 3$ ).

multiple resonance dips, consistent with the multimode coupling characteristics of conventional gratings. However, a key distinction lies in the helical sampling grating exhibiting strong mode-selective coupling: at each specific diffraction-order wavelength (e.g., channels corresponding to topological charges  $l = -3, -2, -1, +1, +2, +3$ ), only one resonance dip exhibits significantly greater depth, while coupling of other modes within that channel is strongly suppressed (indicated by black circles in the figure). As clearly visualized in the mode profiles accompanying each highly resonant dip in Figs. 3(c)–3(h), this selective coupling results in the generation of high-quality OAM modes. Experimental results demonstrate that the spiral sampling grating imposes a stringent angular momentum matching selection rule ( $\Delta l = ml$ ) through its embedded helical phase. This rule forces energy within each diffraction channel to couple efficiently only to specific OAM modes satisfying the matching condition. This achieves wavelength channelization (comb-like spectrum) while simultaneously enabling deterministic mapping and high-purity generation from wavelength to OAM mode.

To precisely characterize the spectral properties of helical sampling fiber Bragg gratings (HS-FBGs) and their excited orbital angular momentum (OAM) modes, we constructed a reflective measurement system, as shown in Fig. 4(a). The signal light (red beam) emitted by the tunable laser passes through a collimator (Col1) before being reflected by beam splitter (BS1). After reflection by BS2, it is coupled into the

HS-FBG via collimator (Col2). The reflected light (blue beam path) retraces its path, sequentially passes through Col2 and BS2, and then is transmitted through BS1. It is subsequently split by beam splitter (BS3) into two paths: one directed to a power meter for recording the reflected spectrum, and the other guided to beam splitter (BS4). Simultaneously, the beam transmitted through BS1 serves as the reference light. After passing through a lens and a neutral density filter (NDF), it is also directed to BS4. The two beams interfere at BS4, and the resulting interference beam (green optical path) is detected by a CCD. By flexibly controlling the presence or absence of the reference optical path, this device can be used to observe either the interference pattern of OAM modes or the direct mode field distribution.

Figure 4(b) shows the experimentally measured reflectance spectrum (red curve) compared with the transmittance spectrum (blue curve) of HS-FBG with a sampling period of  $53.50 \mu\text{m}$ . From short to long wavelengths, the nine clearly discernible resonance dips in the transmission spectrum have center wavelengths of 1491.28, 1507.32, 1523.44, 1539.40, 1555, 1569.96, 1584.48, 1598.72, and 1612.92 nm. The two spectra exhibit a clear overall correspondence, with the distribution pattern of the reflection peaks aligning with the loss structure of the transmission spectrum. Together, they characterize the comb-filtering response introduced by helical sampling. Based on the characteristic resonance wavelengths identified from the reflection spectra in Fig. 4(b), we conducted



**Fig. 4.** Comprehensive characterization of HS-FBG: (a) experimental optical setup diagram for OAM mode analysis in reflection mode; (b) transmission and reflection spectra; (c) OAM mode field distributions and interference patterns excited at different resonant wavelengths.

OAM mode field tests at the corresponding wavelengths. Figure 4(c) sequentially shows the output light field intensity distributions (top row) recorded by the CCD and their interference patterns with the reference light (bottom row) at the seven characteristic wavelengths corresponding to the sampling orders  $m = -3, -2, -1, 0, 1, 2$ , and  $3$ . All intensity distributions show a ring structure with zero central intensity, which is a typical feature of OAM beams. The interference patterns display clear spiral fringes, with the spiral direction and the number of fringes varying systematically with the sampling order  $m$ . These spiral fringes are direct evidence of the interference between vortex beams carrying topological charge  $l = m$  and a spherical reference beam, confirming that the output beam possesses a helical phase structure of  $l = m$ . The above results fully validate the deterministic mapping relationship between resonant wavelength, sampling order, and OAM order.

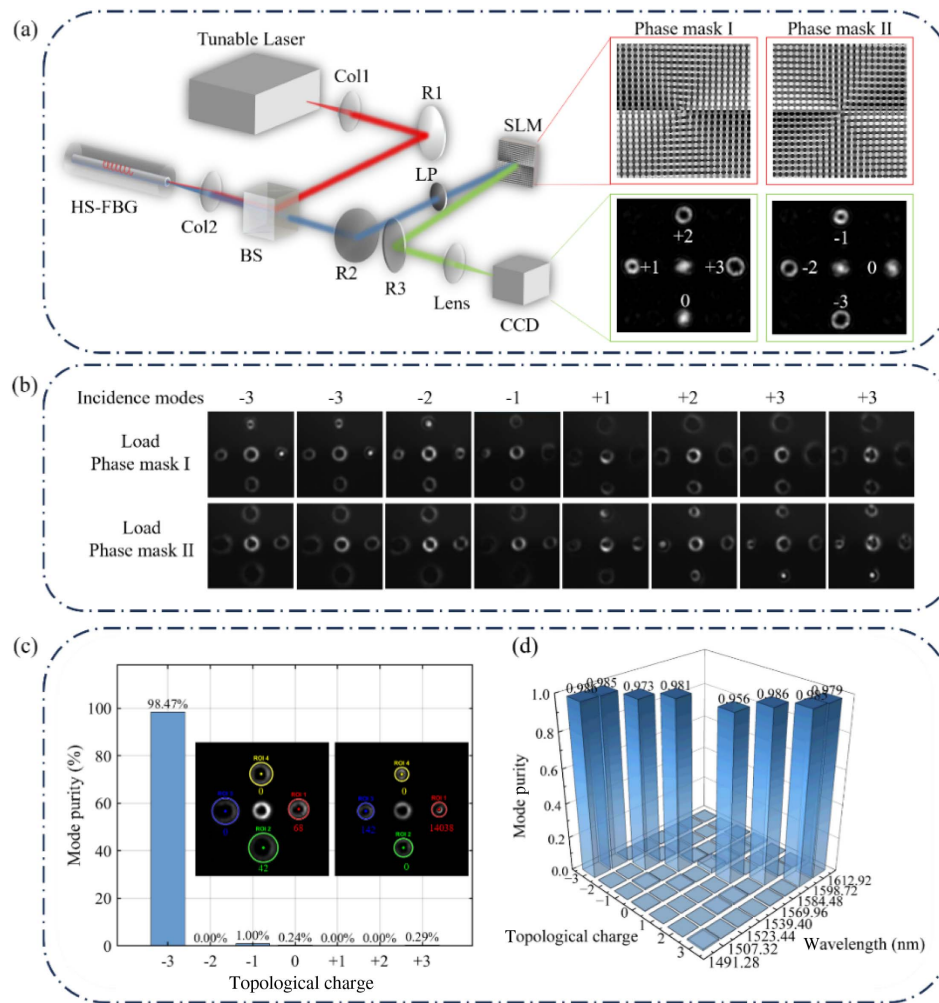
It is worth noting that Fig. 4(c) shows the mode fields of nine channels, where the shortest and longest wavelengths do not correspond to  $\pm 4$  sampling orders. These two channels originate from the incident  $LP_{21}$  mode, which arises from imperfect splicing between the single-mode fiber and the ring-core fiber. In a conventional uniform FBG [Fig. 3(a)], the shortest-wavelength resonance dip arises from coupling between the incident  $LP_{21}$  mode and the backward  $LP_{31}$  mode, as confirmed by mode effective indices and coupled-mode analysis. In the proposed HS-FBG, the helical sampling function introduces an additional angular momentum selection rule. For the  $LP_{21}$  mode input, its net orbital angular momentum for the coupling process is  $l_{in} = 0$ . According to Eq. (6) with  $l_s = 1$ , the output OAM topological charge equals the sampling order  $m$ . Hence, for  $m = \pm 3$ , we obtain  $l_{out} = \pm 3$  (corresponding to  $LP_{31}$  modes). Therefore, the same physical coupling channel ( $LP_{21}$  to  $LP_{31}$ ) that exists in a conventional FBG is mapped to the sampling order  $m = \pm 3$  in the HS-FBG. However, in the conventional grating spectrum, no strong resonance dip is observed at the corresponding wavelengths for such couplings under the same phase-matching condition. Consequently, the HS-FBG inherits the mode-coupling characteristics of the underlying uniform grating, and only the  $\pm 3$  orders are prominently excited for the  $LP_{21}$  input. This interpretation is fully consistent with both the conventional grating reference [Fig. 3(a)] and the angular momentum conservation principle.

The dominance of the  $\pm 3$  orders for the  $LP_{21}$  input is attributed to the specific Fourier coefficients of the helical sampling function; other sampling orders (e.g.,  $\pm 1, \pm 2$ ) are not prominently excited under our experimental conditions. Therefore, these two channels belong to the 3rd-order sampling channels for incident light in the  $LP_{21}$  mode, and their positions also satisfy  $\lambda_m = (n_{eff}^{in} + n_{eff}^{out}) / (2/\Lambda_g - m/\Lambda_g)$ . This phenomenon does not contradict the theoretical mechanism but, rather, further confirms the principle of phase matching.

It has been intuitively confirmed that HS-FBG can selectively excite specific target OAM modes ( $l = ml_s$ ) in different channels. However, while interferograms can identify the main mode, they cannot accurately quantify the energy proportion of the main mode or determine the presence of unwanted stray modes. In practical applications, such as mode-division multiplexing communication, mode purity (i.e., the OAM

spectrum) is a key metric for evaluating device performance and assessing channel crosstalk. The conjugate interference method (also known as the phase-mask method) is employed here because it provides direct, quantitative, mode-resolved analysis without requiring a separate reference beam and is less sensitive to alignment errors compared to other techniques [31]. Therefore, this subsection will use the conjugate phase summation method to calculate purity and quantitatively evaluate the OAM modes generated by the HS-FBG in each channel.

Figure 5 illustrates the experimental setup and results for testing the purity of OAM modes using the conjugate interference method. Figure 5(a) shows a schematic diagram of the experimental setup. The signal light emitted from the tunable laser is reflected by the grating and then is modulated by the spatial light modulator (SLM) before being focused onto the CCD by a lens for imaging. Two types of phase masks are loaded onto the SLM: phase mask I encoded helical phases from 0 to  $+3$  orders ( $l = 0, +1, +2, +3$ ) in sequence, arranged clockwise from bottom to top; phase mask II encoded helical phases from  $-3$  to 0 orders ( $l = -3, -2, -1, 0$ ) in the same clockwise arrangement. The diffracted light fields generated by different masks undergo lens transformation, and their far-field intensity distributions are recorded by a CCD camera. The lower right panel of Fig. 5(a) displays typical far-field intensity distributions obtained with two phase masks when incident with fundamental-mode Gaussian light. Multiple discrete spots correspond to diffraction orders of different OAM orders. Figure 5(b) shows the experimental results of purity testing for specific OAM modes ( $l = -3, -2, -1, +1, +2, +3$ ) generated by the HS-FBG using the aforementioned apparatus. The testing principle is based on conjugate phase interference. For an incident OAM mode with topological charge  $l_{mode}$ , when superimposed with a loaded helical phase of topological charge  $l_{mask}$ , the phase factor of the composite light field is given by  $\exp(i(l_{mode} + l_{mask})\phi)$ . When the two are conjugate, i.e., when  $l_{mode} = -l_{mask}$  is satisfied, the composite phase  $\exp(i0\phi) = 1$  corresponds to a flat wavefront. Consequently, at the diffraction-level position in the far field, light converges into a centrally bright, quasi-Gaussian spot. Conversely, for non-conjugate orders ( $l_{mode} \neq -l_{mask}$ ), the superimposed beam carries net orbital angular momentum ( $l_{sum} = l_{mode} + l_{mask} \neq 0$ ), with a helical wavefront. This results in a ring-shaped intensity distribution in the far field, characterized by zero central intensity and varying ring sizes, as illustrated in the figure. For each incident mode under test, the two sets of intensity distribution maps recorded after loading phase masks I and II, respectively, provide a visual representation of the relative intensities of the OAM components within that mode. This serves as direct evidence for subsequent quantitative calculations of mode purity. Figure 5(c) details the method for calculating mode purity based on the results from Fig. 5(b). Taking the  $l = -3$  incident mode on the left as an example, first, the Hough circle transformation is applied to the two obtained far-field intensity maps to automatically identify all diffraction spots except the central 0th-order diffraction (the Hough circle transformation is a standard image processing algorithm used to automatically detect circular patterns in images). Second, the intensity value at the center of each



**Fig. 5.** Characterization of OAM mode purity based on conjugate interference with a spatial light modulator. (a) Schematic of the experimental setup; (b) far-field spot distributions for incident OAM modes ( $l = -3, \dots, +3$ ) under different phase masks (phase mask I/II); (c) statistical analysis of calculated OAM mode purity for (c)  $-3$ rd and (d) each order.

identified spot is extracted. For the 0th-order intensity present in both masks, its average value is taken as the intensity of the 0th-order component. Thus, the intensity contributions for the seven orders  $l = -3, -2, -1, 0, +1, +2$ , and  $+3$  in this incident light are obtained, enabling the calculation of the mode purity.

The bar chart of Fig. 3(c) quantitatively displays the measured purity of each OAM mode. The calculation method is as described earlier. Taking the  $l = -3$  incident mode as an example, when superimposed with the conjugate phase of  $l = +3$  in phase mask I, a prominent Gaussian-like spot appears at the corresponding far-field position. Calculations show that the intensity contribution at this location reaches 98.47%, representing the quantified purity of this mode. The bar chart summarizes the purity of all tested modes. The specific data are shown in the Table 1. The normalized purity measured at the corresponding wavelengths is all above 95%, indicating that the generated OAM modes possess extremely high purity.

In summary, this work demonstrates a low-loss, high-purity orbital angular momentum (OAM) mode comb generator based on a helical-sampled fiber Bragg grating (HS-FBG) inscribed on a ring-core fiber. The device employs a helical

sampling structure to simultaneously generate multiple OAM modes (from  $-3$  to  $+3$  orders) with purities exceeding 95%, achieved through precise binding between wavelength channels and OAM orders via angular momentum conservation. This approach overcomes the channel bottleneck of existing fiber-grating-based generators while maintaining fiber compatibility and low insertion loss. The results validate the potential of HS-FBGs for high-dimensional mode division multiplexing in practical communication systems. Future efforts could focus on extending the comb bandwidth or supporting higher-order modes for enhanced capacity. To this end, we plan to carry out numerical simulations to gain deeper insights into the coupling dynamics of the HS-FBG and to explore the generation of higher-order OAM modes.

## APPENDIX A: THEORETICAL DERIVATION OF THE HS-FBG MODEL

### 1. Physical Model of the Helical Sampling

The HS-FBG is fabricated by femtosecond laser direct writing along a helical trajectory inside the ring-core

**Table 1. OAM Modes Excited at Different Wavelengths and Their Normalized Purity Measurement Results**

|                   |                  |                  |                  |                  |                  |                  |                  |                  |
|-------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| Wavelength (nm)   | 1491.28          | 1507.32          | 1523.44          | 1539.40          | 1569.96          | 1584.48          | 1598.72          | 1612.92          |
| Input mode        | LP <sub>21</sub> | LP <sub>01</sub> | LP <sub>01</sub> | LP <sub>01</sub> | LP <sub>01</sub> | LP <sub>01</sub> | LP <sub>01</sub> | LP <sub>21</sub> |
| Sampling order    | -3               | -3               | -2               | -1               | 1                | 2                | 3                | 3                |
| Topologic charge  | -3               | -3               | -2               | -1               | 1                | 2                | 3                | 3                |
| Normalized purity | 0.986            | 0.985            | 0.973            | 0.981            | 0.956            | 0.986            | 0.985            | 0.979            |

fiber. In cylindrical coordinates  $(r, \phi, z)$ , the helix is described by

$$\phi_{\text{helix}}(z) = -\frac{2\pi l_s}{\Lambda_s} z, \quad (\text{A1})$$

where  $\Lambda_s$  is the sampling period (axial distance for one complete turn of the helix) and  $l_s$  is an integer called the helical topological charge (number of  $2\pi$  rotations per sampling period; its sign indicates the handedness). The minus sign in Eq. (A1) reflects the actual writing direction used in our experiment, which is essential to reproduce the observed wavelength order.

The refractive index perturbation  $\delta_n$  is confined around this helix. In the transverse plane, the angular distribution of the index change is described by a function  $g(\theta)$  with  $\theta = \phi - \phi_{\text{helix}}(z)$ . The overall index modulation reads

$$\delta_n(r, \phi, z) = \Delta n_{\text{ac}} \cdot h(r - R_{\text{core}}) \cdot g\left(\phi + \frac{2\pi l_s}{\Lambda_s} z\right) \cdot \cos\left(\frac{2\pi}{\Lambda_g} z\right), \quad (\text{A2})$$

where  $\Delta n_{\text{ac}}$  is the modulation depth,  $h(r - R_{\text{core}})$  is the radial profile (nearly constant across the ring core), and  $\Lambda_g$  is the Bragg grating period.

## 2. Fourier Series of $g(\theta)$ and Two-Dimensional Fourier Series

Since  $g(\theta)$  is  $2\pi$ -periodic, it can be expanded as

$$g(\theta) = \sum_{n=-\infty}^{\infty} A_n e^{in\theta}, \quad A_n = \frac{1}{2\pi} \int_0^{2\pi} g(\theta) e^{-in\theta} d\theta. \quad (\text{A3})$$

Substituting  $\theta = \phi + \phi_{\text{helix}}(z)$  gives

$$g\left(\phi + \frac{2\pi l_s}{\Lambda_s} z\right) = \sum_{n=-\infty}^{\infty} A_n \exp\left(in\phi + in\frac{2\pi l_s}{\Lambda_s} z\right). \quad (\text{A4})$$

## 3. Two-Dimensional Fourier Series

Now consider  $\sigma(z, \phi) \equiv g\left(\phi + \frac{2\pi l_s}{\Lambda_s} z\right)$  as a function of two variables,  $z$  periodic with period  $\Lambda_s$  and  $\phi$  periodic with period  $2\pi$ . Its 2D Fourier series is

$$\sigma(z, \phi) = \sum_{m=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} C_{m,k} \exp\left(im\frac{2\pi}{\Lambda_s} z\right) \exp(ik\phi), \quad (\text{A5})$$

with coefficients

$$C_{m,k} = \frac{1}{\Lambda_s \cdot 2\pi} \int_0^{\Lambda_s} \int_0^{2\pi} g\left(\phi + \frac{2\pi l_s}{\Lambda_s} z\right) e^{-im\frac{2\pi}{\Lambda_s} z} e^{-ik\phi} d\phi dz. \quad (\text{A6})$$

After performing the change of variable  $\theta = \phi + \frac{2\pi l_s}{\Lambda_s} z$  ( $\phi = \theta - \frac{2\pi l_s}{\Lambda_s} z$ , Jacobian = 1), then

$$\begin{aligned} C_{m,k} &= \frac{1}{\Lambda_s \cdot 2\pi} \int_0^{\Lambda_s} \int_0^{2\pi} g(\theta) e^{-im\frac{2\pi}{\Lambda_s} z} e^{-ik\left(\theta - \frac{2\pi l_s}{\Lambda_s} z\right)} d\theta dz \\ &= \left[ \frac{1}{\Lambda_s} \int_0^{\Lambda_s} e^{-i\frac{2\pi}{\Lambda_s}(m-kl_s)z} dz \right] \cdot \left[ \frac{1}{2\pi} \int_0^{2\pi} g(\theta) e^{-ik\theta} d\theta \right]. \end{aligned} \quad (\text{A7})$$

The second bracket is  $A_k$ , and the first bracket equals  $\delta_{m+kl_s, 0}$  (1 if  $m - kl_s = 0$ , else 0). Hence,

$$C_{m,k} = \delta_{m-kl_s, 0} A_k. \quad (\text{A8})$$

Only terms with  $k = m/l_s$  survive. For integer  $k$ ,  $m$  must be a multiple of  $l_s$ . In this work, we take  $l_s = 1$  for simplicity, so  $k = m$ . Substituting back into Eq. (A5),

$$\sigma(z, \phi) = \sum_{n=-\infty}^{\infty} A_n \exp\left(in\frac{2\pi}{\Lambda_s} z\right) \exp(in\phi). \quad (\text{A9})$$

Renaming the coefficient  $c_m \equiv A_m$  and using  $l_s = 1$ , we obtain the compact form,

$$\sigma(z, \phi) = \sum_{n=-\infty}^{\infty} c_n \exp\left[in\left(-\frac{2\pi}{\Lambda_s} z + \phi\right)\right]. \quad (\text{A10})$$

This form directly leads to the correct phase-matching condition (see below).

## 4. Combining with the Bragg Cosine Term

Inserting Eq. (A10) into the full index modulation [Eq. (A2)] and expanding the cosine using Euler's formula, we obtain

$$\begin{aligned} \delta_n(z, \phi) &= \Delta n_{\text{ac}} \sum_m c_m e^{im\left(-\frac{2\pi}{\Lambda_s} z + \phi\right)} \cdot \frac{1}{2} \left( e^{i\frac{2\pi}{\Lambda_g} z} + e^{-i\frac{2\pi}{\Lambda_g} z} \right) \\ &= \frac{\Delta n_{\text{ac}}}{2} \sum_m c_m \left[ e^{i\left(\frac{2\pi}{\Lambda_g} - m\frac{2\pi}{\Lambda_s}\right)z + iml_s\phi} + e^{i\left(-\frac{2\pi}{\Lambda_g} - m\frac{2\pi}{\Lambda_s}\right)z + iml_s\phi} \right]. \end{aligned} \quad (\text{A11})$$

The first term (positive sign on the Bragg part) describes coupling between a forward-incident mode and a backward-reflected mode—the dominant process in a reflection grating. The second term corresponds to non-phase-matched processes. Keeping only the phase-matched term and absorbing the factor  $\frac{\Delta n_{\text{ac}}}{2}$  into  $\kappa_m$ , we obtain

$$\delta_n(z, \phi) = \sum_m \kappa_m \exp\left[i\left(\frac{2\pi}{\Lambda_g} - m\frac{2\pi}{\Lambda_s}\right)z + iml_s\phi\right] + \text{c.c.} \quad (\text{A12})$$

**Table 2. Comparison of Experimental and Theoretical Resonance Wavelengths ( $N = 100$ , Using Wavelength Dependent Effective Indices from Simulations)**

| $m$ | $\lambda_{\text{exp}}$ (nm) | $n_{\text{eff}}^{\text{in}}$ | $n_{\text{eff}}^{\text{out}}$ | $\lambda_{\text{th}}$ (nm) | Deviation (nm) |
|-----|-----------------------------|------------------------------|-------------------------------|----------------------------|----------------|
| -3  | 1507.32                     | 1.4551918                    | 1.4490943                     | 1508.65                    | +1.33          |
| -2  | 1523.44                     | 1.4549522                    | 1.4518700                     | 1525.11                    | +1.67          |
| -1  | 1539.40                     | 1.4547145                    | 1.4538089                     | 1540.74                    | +1.34          |
| 0   | 1555.00                     | 1.4544815                    | 1.4544815                     | 1556.29                    | +1.29          |
| 1   | 1569.96                     | 1.4542574                    | 1.4533078                     | 1571.27                    | +1.31          |
| 2   | 1584.48                     | 1.4540392                    | 1.4507011                     | 1585.77                    | +1.29          |
| 3   | 1598.72                     | 1.4538247                    | 1.4470569                     | 1600.04                    | +1.32          |

**Table 3. Comparison of Experimental and Theoretical Adjacent Channel Spacings for  $N = 100$** 

| $m$ Pair | $\Delta\lambda_{\text{exp}}$ (nm) | $\Delta\lambda_{\text{th}}$ (nm) | Deviation |
|----------|-----------------------------------|----------------------------------|-----------|
| -3 & -2  | 1523.44 - 1507.32 = 16.12         | 1525.11 - 1508.65 = 16.46        | +2.1%     |
| -2 & -1  | 1539.40 - 1523.44 = 15.96         | 1540.74 - 1525.11 = 15.63        | -2.1%     |
| -1 & 0   | 1555.00 - 1539.40 = 15.60         | 1556.29 - 1540.74 = 15.55        | -0.3%     |
| 0 & 1    | 1569.96 - 1555.00 = 14.96         | 1571.27 - 1556.29 = 14.98        | +0.1%     |
| 1 & 2    | 1584.48 - 1569.96 = 14.52         | 1585.77 - 1571.27 = 14.50        | -0.1%     |
| 2 & 3    | 1598.72 - 1584.48 = 14.24         | 1600.04 - 1585.77 = 14.27        | +0.2%     |

### 5. Phase-Matching Conditions and Resonance Wavelengths

From Eq. (A12), the axial phase-matching condition for a second-order Bragg grating ( $q = 2$ ) is

$$\beta_{\text{out}} + \beta_{\text{in}} = 2\frac{2\pi}{\Lambda_g} - m\frac{2\pi}{\Lambda_s}. \quad (\text{A13})$$

Using  $\beta = 2\pi n_{\text{eff}}/\lambda$ , we obtain the corrected resonance wavelength formula:

$$\lambda_m = \frac{n_{\text{eff}}^{\text{in}} + n_{\text{eff}}^{\text{out}}}{\frac{2}{\Lambda_g} - \frac{m}{\Lambda_s}}. \quad (\text{A14})$$

The azimuthal (angular) phase matching follows from the integral  $\int_0^{2\pi} e^{i(l_{\text{out}} - l_{\text{in}} - ml_s)} d\phi$ , which gives

$$l_{\text{out}} - l_{\text{in}} = ml_s. \quad (\text{A15})$$

Tables 2 and 3 summarize the difference between the experiment and theoretical results.

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**Data Availability.** Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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