

INTERFERENCE-BASED MODAL SELECTION IN A FINITE MULTILAYER RING-CORE WAVEGUIDE

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Abstract. Selective transmission of a prescribed orbital angular momentum (OAM)-compatible guided family in a ring-core fiber is complicated by neighboring vector modes with comparable propagation characteristics. We consider a finite, longitudinally uniform multilayer ring-core segment in which the radial refractive-index profile controls phase accumulation and subsequent recombination of guided modal components. The structure is described using a full-vector cylindrical Maxwell model combined with interface mode matching and an open-guided treatment of radiative components. For the optimized five-layer segment at $\lambda=1550$ nm, the selected HE_{21} -based OAM-compatible guided family reaches a same-mode guided output transmission of $T_l \approx 0.83$, whereas the largest transmission among the competing HE_{11} , TE_{01} , and TM_{01} modes is $T_{\text{worst}} \approx 0.01$. This corresponds to a modal extinction ratio (MER) of 19.28 dB. The calculated waveguide/modal selectivity interval is approximately 1548.254–1554.432 nm under fixed refractive indices, while fabrication-induced detuning can be partly compensated by adjusting the segment length. These results demonstrate that a finite-length radially multilayered ring-core fiber section can provide interference-based selective transmission of a prescribed guided modal family.

Keywords: ring-core fiber, orbital angular momentum, multilayer waveguide, modal interference, mode selectivity

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1. Introduction

Orbital angular momentum (OAM) states of light have attracted considerable attention as an additional degree of freedom for transmitting and processing optical information. In optical fibers, these states are associated with guided vector modes that exhibit an annular field distribution and an azimuthally varying phase. More generally, characterizing spatially complex optical fields requires access not only to their intensity distribution but also to their phase structure; correlation-based approaches have been demonstrated to reconstruct complex scalar optical fields and identify phase singularities [1]. Ring-core fibers are particularly suitable for supporting vortex-compatible guided states because their annular guiding region is naturally matched to the transverse structure of these optical fields [2–4]. Experimental studies have demonstrated OAM-based mode-division multiplexing in specially designed fibers, and subsequent work has shown that ring-core fibers can support multiple OAM mode groups over propagation distances relevant to optical communication systems [3,5]. These results established the practical possibility of transmitting vortex-compatible states in fibers, but they also highlighted an important problem: increasing the number of supported spatial states simultaneously increases the requirements for controlling the modal spectrum and suppressing unwanted mode coupling. Bozinovic et al.

provided an early experimental demonstration of OAM mode-division multiplexing in fiber, and Brunet et al. subsequently developed a family of ring-core fibers specifically for OAM transmission studies [3,4].

The properties of OAM-compatible states in a fiber are determined not only by the presence of an annular guiding region but also by the radial refractive-index profile. Changes in ring geometry and $n(r)$ modify the effective refractive indices, cutoff conditions, radial localization, and separation between the vector eigenmodes. This provides a direct means to engineer the supported modal spectrum. For example, graded-index ring-core fibers have been designed to support only the first radial order across several mode groups, thereby reducing the number of unwanted radial states [6]. Large differences in effective refractive index between mode groups have also been used to reduce inter-group coupling in long-distance OAM transmission [5]. More recently, the radial profile itself has been treated as an additional design degree of freedom. A two-layer ring-core structure was shown to increase the separation between vector eigenmodes and weaken spin-orbit coupling [7], whereas a fabricated dual-step-index ring-core fiber suppressed spin-orbit coupling and cut off higher-radial-order modes while supporting high-order OAM states [8]. A parabolic graded-index profile has likewise been used to improve OAM-mode purity by reducing mode mixing associated with abrupt refractive-index changes [9]. These studies provide direct evidence that radial refractive-index engineering can be used not only to guide OAM-compatible modes but also to control which modal families are supported and how strongly they interact [6-9].

A related direction is based on multilayer, Bragg-type, and interferometric fiber structures. Bai et al. demonstrated that periodic high/low-index radial structuring can strongly modify the OAM-supporting modal spectrum of an annular waveguide, while more recent multilayer and antiresonant ring-core designs have used several radial index regions to control confinement, radial-order content, and modal loss [10,11]. These approaches primarily exploit the radial refractive-index profile to determine which modes are supported, their confinement properties, cutoff conditions, and effective-index separation.

Finite-length multimode interference has also been used for OAM generation and manipulation in fiber. Zhou showed that multimode interference in a ring-core fiber can transform an input field into multiple azimuthally distributed output images; after additional phase correction by a fixed phase-shifter array, these images can be used for OAM generation or detection [12]. More recently, Wu et al. demonstrated an in-fiber mode-selective interferometer formed by two long-period fiber gratings separated by a finite distance. In that configuration, the first grating selectively couples the fundamental mode to a prescribed higher-order mode; the two modes accumulate a relative phase during propagation; and the second grating recombines them, enabling wavelength-selective OAM conversion and switching [13].

The present work addresses a different interference architecture. No longitudinal grating, discrete mode-selective coupler, external phase-shifter array, or active modulation is used. Instead, a longitudinally uniform radially multilayered ring-core section is inserted between two identical reference ring-core fibers. At the first longitudinal interface, a launched reference-fiber mode decomposes into several symmetry-compatible guided vector eigenmodes of the multilayer section. These modes acquire different phases according to their propagation constants over the finite length L , and at the second interface they are coherently projected back onto the guided modes of the reference fiber.

Consequently, the radial refractive-index profile and the physical length serve distinct but coupled functions. The radial profile determines the modal basis, excitation amplitudes, and propagation constants, whereas the finite length controls their relative phase accumulation. Modal discrimination is therefore not achieved solely by cutting off unwanted modes or by maximizing the confinement of the target mode. A competing reference-fiber mode may remain fully guided in the structure yet be weakly reconstructed at the output because its internal modal contributions interfere destructively or only weakly coherently. Conversely, the target mode is preferentially recovered when its dominant internal contributions recombine constructively.

The specific contribution investigated here is the use of a finite, longitudinally uniform, radially multilayered ring-core section as a passive guided-mode interferometric selector for a prescribed OAM-compatible modal family. The design problem is formulated jointly in terms of the radial multilayer geometry and the finite propagation length, and the resulting selectivity is evaluated against the reference fiber's complete set of competing guided modes.

An additional consequence of this formulation is that higher-order radial eigenmodes of the intermediate multilayer section are not necessarily parasitic. They can act as coherent propagation components whose amplitudes and accumulated phases contribute to reconstructing the prescribed output state. The design objective is therefore not simply to eliminate higher-order modes, but to control their participation in the finite-length interference process.

In this work, this principle is examined to select an HE_{21} -based OAM-compatible guided family at a wavelength of 1550 nm. The analysis uses a full-vector Maxwell formulation for cylindrically stratified dielectric media because the relevant HE , TE , and TM modes and their separation cannot be reliably described within the scalar linearly polarized (LP) mode approximation. The resulting eigenmodes are combined with interface mode matching to calculate the propagation and recombination of the guided components through a finite multilayer segment. The numerical procedure is validated against published ring-core-fiber eigenvalues and by an independent finite-element check. The optimized structure is then evaluated for transmission of the target HE_{21} -based family and the competing HE_{11} , TE_{01} , and TM_{01} modes. Finally, the spectral response, segment-length sensitivity, and fabrication perturbations are examined to establish both the achievable modal selectivity and the limitations of the proposed interference-based filtering mechanism.

2. Physical principle and problem formulation

The physical system considered in this work consists of a conventional ring-core fiber, a finite radially multilayered section, and the same ring-core fiber at the output. The input field is therefore not an independently specified free-space beam but a known guided mode of the reference fiber. At the first interface, this mode excites a set of vector eigenmodes of the multilayer section. These components propagate with different propagation constants and accumulate different phases over the finite length of the section. At the second interface, they are projected back onto the guided modes of the reference fiber. The operating principle considered below is based on controlling this decomposition, phase accumulation, and subsequent modal recombination. The individual elements of this configuration and the corresponding modal-selection mechanism are introduced separately below.

2.1. Reference ring-core fiber and target guided family

The reference ring-core fiber (RCF) defines both the launched modes and the guided states analyzed at the output. Its annular core is bounded by the inner and outer radii $a_{ref}=1.09\ \mu\text{m}$ and $b_{ref}=3.11\ \mu\text{m}$, with refractive indices $n_{ring}=1.474$ and $n_{clad}=1.444$ [3]. The nominal design wavelength is $\lambda=1550\ \text{nm}$. These parameters correspond to the Fiber 3 ring-core configuration reported by Brunet et al. [4] and are used here as the reference RCF for both the launched and output guided modes. The geometry and radial refractive-index profile of the reference RCF are shown in Fig. 1.

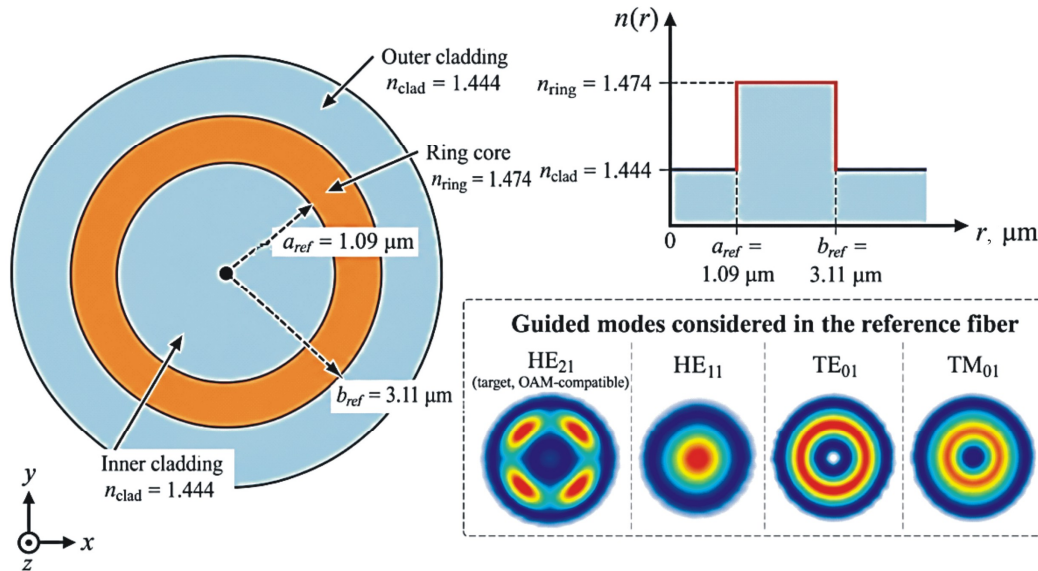


Fig. 1. Reference ring-core fiber used to define the launched and output guided modes. The high-index annular core, $n_{ring}=1.474$, extends from the inner radius $a_{ref}=1.09\ \mu\text{m}$, to the outer radius $b_{ref}=3.11\ \mu\text{m}$ and is surrounded on both sides by cladding with $n_{clad}=1.444$. The corresponding radial refractive-index profile and the guided modal families considered in the modal-selection analysis are also shown.

These parameters correspond to the reference RCF used throughout the modal analysis and numerical validation. The final notation and dimensions are fixed in the Supplementary Materials and are used consistently below.

The guided state selected as the target is the HE_{21} -based OAM-compatible family. In the OAM notation used here, it corresponds to $(|l|, m) = (1, 1)$, where l denotes the OAM-compatible azimuthal phase label, and m is the radial order. The other guided modes considered as competitors are HE_{11} , TE_{01} , and TM_{01} modes. These four input states therefore define the modal-selection problem investigated in the present work.

Distinguishing between the azimuthal indices used in the vector eigenproblem and in the OAM description is important. The symbol v is used below for the azimuthal order of the full-vector cylindrical eigenproblem, whereas l is reserved for the OAM-compatible phase label. The two symbols should therefore not be treated as interchangeable. For the target considered here, the HE_{21} vector family is associated with the first-order OAM-compatible state $|l|=1$. The adopted notation also reflects the symmetry of the physical structure: because the refractive-index profile is axisymmetric and reciprocal, it does not distinguish between the $+l$ and $-l$ members of the corresponding OAM-compatible pair.

The term OAM-compatible guided family is used deliberately. A ring-shaped intensity distribution alone is insufficient to identify a vortex state. A vortex-compatible field must also exhibit the corresponding azimuthal phase winding. In addition, the present calculations do not model the propagation or focusing of a free-space vortex beam onto the fiber end face. The launched fields are eigenmodes of the reference RCF, and the problem addressed here is their transformation by a finite guided-wave structure. This distinction is consistent with the full-vector description of ring-core modes, in which annular localization and azimuthal phase structure are distinct physical properties.

2.2. Radially multilayered finite section

The mode-selective section is a passive, cylindrically symmetric and longitudinally uniform waveguide segment. Its refractive-index distribution depends on the radial coordinate r but is independent of the azimuthal coordinate and, inside the segment, of the longitudinal coordinate. The radial structure consists of five concentric layers arranged as $H-L-H-L-H$, where H and L denote regions with high and low refractive indices, respectively.

The inner radius of the multilayer region is $a=2.15\mu\text{m}$, and its total radial width is $W=4.00\mu\text{m}$. The five layer thicknesses are $(d_1, d_2, d_3, d_4, d_5) = (0.672, 0.528, 1.600, 0.528, 0.672)\mu\text{m}$, so that $W = \sum_{j=1}^5 d_j$. The refractive indices are $n_H=1.520$, $n_L=1.444$. The low-index value is also used for the surrounding cladding regions. The nominal physical length of the optimized segment is $L=2.025\text{mm}$. Fig. 2 summarizes the transverse geometry, radial refractive-index profile, layer thicknesses, and longitudinal arrangement of the finite multilayer section.

These parameters define the five-layer structure used in all nominal, spectral, and fabrication-sensitivity calculations reported below. For convenience, the radial boundaries may be written as $r_0=a$, $r_j=a+\sum_{k=1}^j d_k$, $j=1, \dots, 5$. The corresponding piecewise-

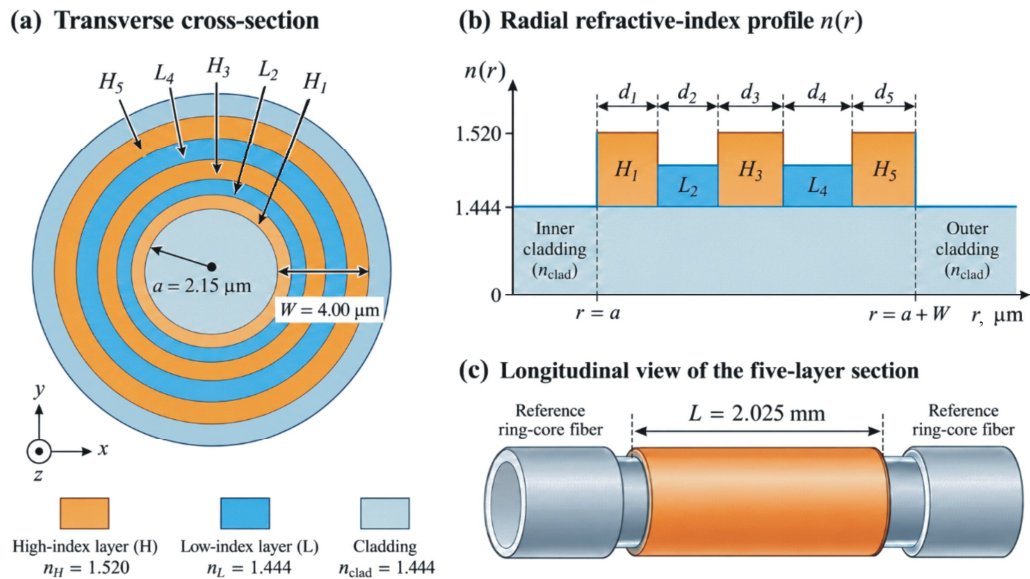


Fig. 2. Geometry and refractive-index profile of the optimized five-layer ring-core fiber section. (a) Transverse cross-section showing the inner radius of the multilayer region, $a=2.15\mu\text{m}$, and its total radial width, $W=4.00\mu\text{m}$. (b) Radial refractive-index profile $n(r)$ with the individual layer thicknesses d_1-d_5 , the layer sequence $H-L-H-L-H$, and the boundaries at $r=a$ and $r=a+W$. The high- and low-index values are $n_H=1.520$ and $n_L=1.444$, respectively. (c) Longitudinal arrangement of the finite multilayer section ($L=2.025\text{mm}$) between two reference ring-core fiber segments.

constant radial profile $n(r)$ therefore contains several annular regions in which the allowed vector modes have different radial field distributions and effective refractive indices. The segment is not tapered along z , and no active modulation is introduced. Consequently, once the structure has been specified, its longitudinal action is determined by the propagation constants of its eigenmodes and by the finite physical length L .

This distinction is central to the proposed concept. The multilayer profile is introduced not only to change cutoff conditions or support a different number of modes. Its purpose is to form an intermediate modal space in which an incident reference-fiber mode is represented by several coherent guided components. The radial geometry determines the composition of this representation, whereas the segment length determines how the relative phases of these components evolve before they reach the second interface.

2.3. Interference mechanism of modal selection

Let q denote a guided mode launched from the reference RCF. At the first interface, its field is expressed in the guided eigenmode basis of the multilayer section. If $F_p(r, \phi)$ is the field distribution of the p -th guided mode of this section and a_{qp} is the corresponding excitation coefficient, the field immediately after the interface can be written as

$$E_q^{(seg)}(r, \phi, 0) = \sum_p a_{qp} F_p(r, \phi). \quad (1)$$

After propagation through a segment of length L , each component acquires its own longitudinal phase:

$$E_q^{(seg)}(r, \phi, L) = \sum_p a_{qp} F_p(r, \phi) \exp(i\beta_p L), \quad (2)$$

where

$$\beta_p = k_0 n_{eff,p}, \quad k_0 = 2\pi / \lambda. \quad (3)$$

The propagation constants β_p are generally different. The relative phase between any two participating segment modes, p and s , therefore changes as

$$\Delta\Phi_{ps}(L) = (\beta_p - \beta_s)L. \quad (4)$$

Eqs. (2–4) express the principal physical mechanism considered in this work. The radial profile determines which eigenmodes participate in the expansion and their propagation constants, while L controls their relative phases at the output interface.

The field returning to a particular guided state of the reference RCF is determined by the coherent superposition of these contributions. If β_{rp} denotes the projection coefficient from the p -th segment mode onto the output reference-fiber mode r , the complex amplitude transferred from an input mode q to an output mode r can be written as

$$A_{rq}(L) = \sum_p b_{rp} a_{qp} \exp(i\beta_p L). \quad (5)$$

The physical meaning of Eq. (5) and the corresponding mode-selection mechanism are shown schematically in Fig. 3.

Fig. 3 summarizes the central physical idea of the present work. The multilayer section is not merely a static radial filter, but a finite interference segment in which several excited guided eigenmodes propagate with different phase constants and coherently recombine at the output interface. The target state is selected when these pathways recombine predominantly in phase at the output, whereas the competing states remain only weakly reconstructed.

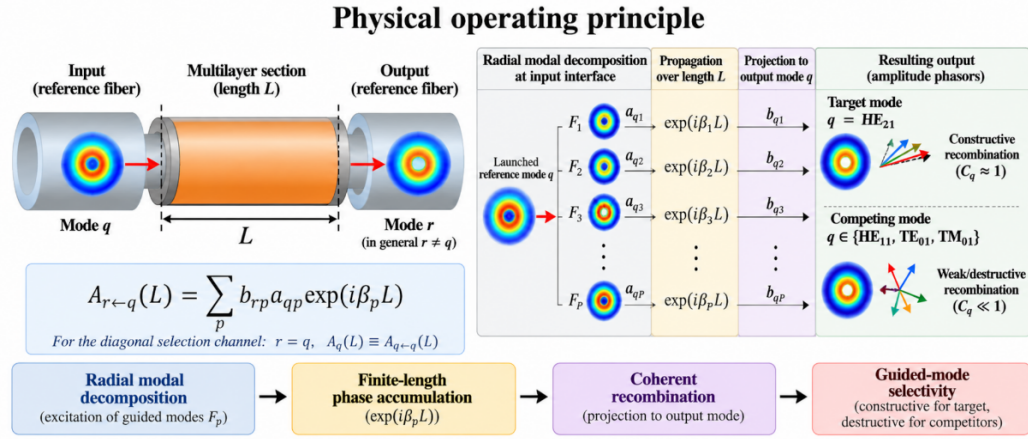


Fig. 3. Interference-based physical operating principle of the finite multilayer modal selector. An input guided mode q of the reference ring-core fiber excites a set of guided eigenmodes F_p of the multilayer section with amplitudes a_{qp} . During propagation over the finite length L , these components accumulate different phase factors $\exp(i\beta_p L)$, where β_p is the propagation constant of the p -th multilayer eigenmode. At the output interface, the propagated components are projected back onto the guided modes of the reference fiber through the coefficients b_{rp} . For the target HE_{21} -based OAM-compatible family, the dominant contributions recombine constructively, whereas for the competing guided modes, the reconstruction is much weaker.

For the corresponding input-output channel $r = q$, we write $A_q(L) \equiv A_{q \leftarrow q}(L)$, and, for power-normalized modes,

$$T_q = |A_q(L)|^2. \quad (6)$$

Here, T_q denotes the guided output power obtained when the reference mode q is launched, normalized to the launched power. This definition is the one adopted throughout the manuscript and in the Supplementary Materials. In particular, $T_t = T_{HE_{21}}$, whereas

$T_{\text{worst}} = \max(T_{HE_{11}}, T_{TE_{01}}, T_{TM_{01}})$. The missing part of the launched power is not interpreted as material absorption; the treatment of non-bound components and the open-guided approximation is specified separately in the numerical model Eq. (5) also shows why the structure's response cannot be understood from the properties of a single intermediate mode. Each reference mode excites its own set of amplitudes a_{qp} , and the corresponding contributions generally have different magnitudes and phases. Therefore, the same multilayer section can produce different interference conditions for HE_{21} , HE_{11} , TE_{01} and TM_{01} .

For the target HE_{21} -based family, the design objective is to find a segment length where the dominant contributions in Eq. (5) are approximately phase-aligned. Their coherent recombination then returns a large fraction of the launched power to the target guided state. For a competing mode, a different set of coefficients and propagation constants is involved. At the same physical length, its contributions can be distributed over the complex plane so that their coherent sum is substantially smaller. Thus, high target transmission and competitor suppression can occur simultaneously even though the segment itself is passive and contains no absorbing or actively switched element.

The role of higher radial modes in this mechanism is therefore different from their usual interpretation as unwanted modal content. Inside the finite multilayer section, a higher-order radial eigenmode can form one of several coherent pathways connecting the

input and output reference states. Its presence is useful when its amplitude and accumulated phase contribute constructively to the target reconstruction or destructively to the reconstruction of a competing state. Consequently, the objective is not to eliminate all intermediate higher-order modes. Instead, it aims to control the full set of participating guided components, so their coherent evolution produces the required output selectivity.

The numerical analysis in the following sections determines whether this condition can be realized for the HE_{21} -based target family and quantifies the resulting selectivity, spectral response, and sensitivity to fabrication parameters.

3. Full-vector model and numerical procedure

The physical mechanism introduced in Section 2 requires determining the propagation constants, field distributions, and interface overlaps of the guided modes with sufficient accuracy to resolve their relative phase evolution. Since the target and competing states belong to different vector-mode families, the analysis is based on the full electromagnetic eigenproblem rather than on a scalar LP approximation. The calculation is performed in two stages. First, we determine the vector eigenmodes of the reference fiber and the multilayer section from Maxwell's equations. Second, these modes are coupled at the two longitudinal interfaces and propagated through the finite section with their individual propagation constants.

3.1. Full-vector cylindrical eigenproblem

The reference fiber and the multilayer section are treated as linear, isotropic, nonmagnetic dielectric waveguides with an axisymmetric refractive-index profile $n(r)$. For the harmonic convention $\exp(-i\omega t)$, Maxwell's equations in each homogeneous layer are written as

$$\nabla \times \mathbf{E} = i\omega\mu_0 \mathbf{H}, \quad (7)$$

$$\nabla \times \mathbf{H} = -i\omega\epsilon_0 n^2(r) \mathbf{E}. \quad (8)$$

Because each uniform section is invariant along the fiber axis and rotationally symmetric, a modal field can be represented as

$$\{\mathbf{E}, \mathbf{H}\}(r, \phi, z) = \{\mathbf{e}, \mathbf{h}\}(r) \exp(i\nu\phi) \exp(i\beta z), \quad (9)$$

where ν is the azimuthal order of the vector eigenproblem, and β is the propagation constant. As specified in Section 2, ν is kept distinct from the OAM-compatible label l .

After substituting Eq. (9) into Maxwell's equations, the six field components reduce to the two longitudinal components E_z and H_z . In a homogeneous layer j , both longitudinal components satisfy radial Bessel equations of the form

$$\left[\frac{d^2}{dr^2} + \frac{1}{r} \frac{d}{dr} + k_0^2 n_j^2 - \beta^2 - \frac{\nu^2}{r^2} \right] \Psi_j(r) = 0, \quad (10)$$

where Ψ_j denotes either E_z or H_z , and $k_0 = 2\pi / \lambda$.

This study uses this formulation as the reference modal framework and extends it to the finite, radially multilayered section considered here.

The corresponding layerwise solutions are combinations of ordinary or modified Bessel functions, depending on whether the radial field is oscillatory or evanescent in the region. This reduction follows the standard full-vector treatment of radially stratified fibers [14–17]; the detailed derivation is omitted here because the present work focuses on modal interference in the finite multilayer section.

In our previous work [18], we presented a detailed Maxwell-based derivation of the vector-mode problem for a three-layer ring-core fiber, including reducing Maxwell's equations to the longitudinal field components, constructing the boundary-condition matrix, and physically interpreting β , n_{eff} , and the azimuthal order.

At each radial interface, the tangential field components E_z , E_ϕ , H_z and H_ϕ are continuous. Applying these continuity conditions at all interfaces relates the expansion coefficients of the field solutions in adjacent layers and yields a homogeneous linear system

$$\mathbf{M}_\nu(\beta)\mathbf{x} = 0. \quad (11)$$

where $\mathbf{M}_\nu(\beta)$ is the boundary-condition matrix for azimuthal order ν and propagation constant β , and $\mathbf{x}$ is the vector of unknown expansion coefficients of the longitudinal field components in all radial layers.

A nontrivial guided-mode solution exists only when the boundary-condition matrix becomes singular, which leads to the characteristic condition

$$\det \mathbf{M}_\nu(\beta) = 0. \quad (12)$$

The physical origin of this condition is straightforward: the field may change its radial functional form between adjacent dielectric layers, but the tangential electromagnetic fields cannot be discontinuous at an ideal dielectric interface.

In the numerical implementation, the guided roots are located from the near-singularity of the boundary matrix rather than by relying only on direct evaluation of its determinant. Once a root has been identified, the associated null-space vector determines the relative layer amplitudes, from which all six electromagnetic field components are reconstructed and power-normalized.

For each eigenmode q , the effective refractive index is defined as

$$n_{eff,q} = \beta_q / k_0, \quad (13)$$

The resulting solutions are classified into the *HE*, *EH*, *TE*, and *TM* vector families according to their field structure and azimuthal order. The same full-vector procedure is used for both the reference RCF and the five-layer intermediate section. The notation $n_{eff,q}$ and β_q is retained consistently throughout the manuscript and Supplementary Materials.

3.2. Interface mode matching and open-guided model

The complete structure contains two longitudinal interfaces and can be represented schematically as *reference RCF* $\rightarrow$ *multilayer section* $\rightarrow$ *reference RCF*.

At the first interface, a power-normalized guided reference mode q is projected onto the eigenmodes of the multilayer section. The modal amplitudes are obtained from the electromagnetic field overlaps, subject to continuity of the transverse fields at the interface. Denoting the bound guided modes of the multilayer section by p , the bound part of the field immediately after the first interface can be written as

$$\mathbf{F}_q^{(+)} = \sum_p a_{qp} \mathbf{F}_p. \quad (14)$$

The coefficients a_{qp} therefore contain both the spatial and vectorial matching between the launched reference mode and the segment eigenmodes.

During propagation through the uniform section, the coefficient of each bound mode acquires the phase factor

$$a_{qp}(L) = a_{qp}(0) \exp(i\beta_p L). \quad (15)$$

At the second interface, the propagated field is projected onto the guided modes of the output reference RCF. If β_{rp} denotes the overlap between segment mode p and output reference mode r , the corresponding guided output amplitude is calculated directly from Eq. (5). Eq. (5) is the numerical form of the interference mechanism introduced in Section 2. The geometry determines a_{qp} , b_{rp} , and β_p , whereas the finite length L controls the relative phases of the terms in the coherent sum. Because the structure and both interfaces are axisymmetric, only symmetry-compatible modal projections are nonzero in the ideal model; Eq. (5) is written in general form, whereas the selectivity reported below is evaluated from the corresponding diagonal channels $r = q$.

For the mode-selective analysis, we use the same-mode guided transmission T_q defined in Eq. (6). Using the notation introduced in Section 2, $T_t = T_{HE_{21}}$, while $T_{worst} = \max(T_{HE_{11}}, T_{TE_{01}}, T_{TM_{01}})$. The modal extinction ratio used to quantify the selectivity is $MER = 10 \log_{10}(T_t/T_{worst})$. Here, T_q denotes the power recovered in the same guided reference-fiber mode q that was launched at the input, normalized to the launched power. Accordingly, $T_{HE_{21}}$, $T_{HE_{11}}$, $T_{TE_{01}}$, and $T_{TM_{01}}$ refer to separate launch conditions and should not be interpreted as modal components of a single output field. The modal extinction ratio MER therefore quantifies the selectivity between the target launch channel and the strongest competing launch channel. It is not a measure of the modal purity of the total output field. Likewise, T_q is not the fraction of mode q in the total transmitted optical power, because the latter may contain other guided and radiative contributions. The present study therefore reports same-mode guided transmission and channel-to-channel modal selectivity, rather than total-output modal purity. In particular, T_q is a guided output power, not a total power-transmission coefficient through all possible radiative and guided channels.

A specific treatment is required for radiation generated at the longitudinal interfaces. A finite numerical transverse domain converts the radiation continuum into a discrete set of box-dependent states. If these artificial states are propagated coherently over the full segment and then allowed to recombine at the second interface, the result can depend on the chosen numerical box radius rather than on the physical fiber.

For this reason, an open-guided approximation is used. At each longitudinal interface, the field is matched using both bound and radiation components, which preserves the interface coupling amplitudes and the associated power balance between reflected, bound-transmitted, and radiation channels. Between the two interfaces, however, only the physically bound guided modes of the multilayer section are propagated coherently. Radiation that has left the finite fiber cladding before reaching the second interface is treated as escaped and is not returned artificially to the output modal projection. Independent interface calculations confirmed near-unity power balance and separated the transmitted field into bound and radiation contributions.

This approximation is particularly appropriate for the millimeter-scale section considered here. For the independently analyzed TM_{01} case, approximately 0.935 of the transmitted power remained in the bound guided subspace, whereas approximately 0.065 was carried by radiation components. These values refer to the independent interface test

case used to validate the open-guided power accounting and should not be interpreted as the power balance of the nominal HE_{21} target-transmission calculation. In particular, the radiative fraction is not obtained as $1 - T_t$. The channel-resolved radiation analysis showed that the largest modeled propagation distance required for a radiative component to reach a cladding radius of $62.5 \mu\text{m}$ is approximately 1.269 mm , which is shorter than the nominal segment length $L = 2.025 \text{ mm}$. Thus, within the adopted radiation-channel model, all modeled outward-propagating radiation components reach the finite-cladding boundary before the second interface and are treated as escaped rather than being returned coherently by an artificial numerical box. Detailed power-accounting and radiation-escape data are provided in Supplementary Data S03–S04 and S19–S20.

3.3. Numerical validation

The numerical procedure was validated before it was applied to the multilayer structure. First, the full-vector eigenproblem was tested against the effective refractive indices reported by Brunet et al. [4] for their ring-core Fiber 3 configuration. The calculated values were $n_{\text{eff}}(HE_{11}) = 1.461475$, $n_{\text{eff}}(TE_{01}) = 1.454426$, $n_{\text{eff}}(TM_{01}) = 1.454091$, and $n_{\text{eff}}(HE_{21}) = 1.454258$. The corresponding reference values are 1.4615, 1.4545, 1.4541, and 1.4543, respectively. The maximum absolute difference is therefore $\max |\Delta n_{\text{eff}}| = 7.36 \times 10^{-5}$, which is sufficiently small for the phase-resolved calculations performed below. An independent finite-element calculation of the TM_{01} mode agreed with the vector boundary solution to within a few 10^{-6} in n_{eff} . The agreement is particularly important because the subsequent modal-interference calculation depends directly on differences between propagation constants rather than only on qualitative modal shapes.

Second, the interface calculation was checked independently for power conservation. For the TM_{01} test case, the sum of reflected and transmitted powers differed from unity by only approximately 3×10^{-4} . This test verifies that the interface decomposition itself does not introduce a significant artificial gain or loss.

Third, the influence of the finite transverse computational boundary was examined. The effective index and bound-mode contribution remained stable as the numerical domain changed, whereas coherent recurrence involving discretized radiation states varied with the box radius. This behavior provides the numerical justification for retaining the stable bound-guided subspace while treating outward-propagating radiation as escaped. The Supplementary Materials contain the detailed eigenvalue benchmark, interface power accounting, and finite-box convergence data.

Taken together, these checks validate the three elements required for the subsequent calculation: the vector eigenvalues and fields, the longitudinal interface matching, and the separation between the bound guided subspace and non-bound radiation components.

The detailed eigenvalue benchmark and independent TM_{01} cross-check are provided in Supplementary Data S01–S02 and Supplementary Fig. S1. Interface power accounting and the open-guided convergence diagnostic are provided in Supplementary Data S03–S04. Supplementary Data S14 provides the complete guided-mode set for the reference fiber, while Supplementary Data S15 provides the compact final validation summary.

4. Design variables and selection criterion

The general multilayer geometry can be parameterized by

$$D = \{R, W, N, d_j, n_j, L\}, \quad (16)$$

where R specifies the radial position of the multilayer guiding region, W is its total radial width, N is the number of radial layers, d_j and n_j are the thickness and refractive index of layer j , and L is the physical length of the finite section. The numerical search was organized hierarchically. Candidate structures were first compared with respect to the radial position and total width of the guiding region, the number of concentric layers, and the distribution of layer thicknesses and refractive indices. For each candidate geometry, the full-vector eigenmodes of the multilayer section were recalculated, the two longitudinal interfaces were matched, and the physical segment length L was scanned as the principal phase-matching variable. Candidate structures were retained only when high target transmission T_t and low worst-competitor transmission T_{worst} were achieved simultaneously; MER alone was not used as the selection criterion. The final five-layer configuration was subsequently subjected to independent wavelength-dependent recalculation, local length-sensitivity analysis, and one-at-a-time fabrication-perturbation tests.

For a structure occupying the radial interval from a to $a+W$, the mean radial position can be written as

$$R = a + \frac{W}{2}. \quad (17)$$

The selected geometry is specified primarily by a and W , because these quantities are used consistently in the Supplementary Materials.

The mode-selective objective is defined with respect to the four guided reference-fiber states identified in Section 2. The optimization seeks to maximize the same-mode guided transmission T_t of the HE_{21} -based OAM-compatible target family while simultaneously minimizing the largest competing same-mode transmission T_{worst} . The modal extinction ratio (MER), defined earlier, serves as a compact measure of the resulting channel selectivity; however, a large MER alone is not sufficient, because a trivial solution with very low transmission for all modes could also produce a large ratio. Therefore, candidate structures are evaluated based on both high target transmission and low worst-competitor transmission.

This quantity is used throughout the remainder of the paper as a channel-selectivity metric and should not be interpreted as the modal purity of a single output field. The same MER definition is used consistently in the Supplementary Materials. The optimization was performed at the nominal wavelength $\lambda_0 = 1550$ nm.

5. Results and discussion

The numerical results are considered in the same order as the physical processes introduced in Sections 2–4. We first examine modal selectivity at the nominal operating point, then analyze its origin in interference and its dependence on segment length. The spectral response and sensitivity to fabrication perturbations are considered afterward. This sequence allows us to distinguish the principal physical effect from the conditions required for its practical realization.

5.1. Nominal modal selectivity

For the optimized five-layer structure described in Section 2.2 and shown in Fig. 2, the open-guided calculation was performed at the nominal wavelength $\lambda_0 = 1550$ nm and the optimized segment length $L = 2.025$ mm.

The calculated same-mode guided-output powers are $T_{HE_{21}} = 0.828891$, $T_{HE_{11}} = 0.009600$, $T_{TE_{01}} = 0.009775$, and $T_{TM_{01}} = 0.006553$. Thus, when the HE_{21} -based OAM-compatible family is launched, approximately 83% of the input power is recovered in the corresponding HE_{21} -based guided output state. In separate calculations in which HE_{11} , TE_{01} , and TM_{01} is launched, the corresponding same-mode guided-output transmission remains below 1%. These values characterize separate diagonal input-output channels and therefore do not constitute a modal decomposition or modal-purity estimate for a single transmitted field.

The strongest competing channel is TE_{01} with $T_{worst} = 0.009775$, corresponding to a modal extinction ratio $MER = 19.28$ dB. These values define the nominal operating point used in the subsequent analysis. An independent wavelength-dependent recalculation at exactly 1550 nm gives $T_t = 0.829661$, $T_{worst} = 0.010564$, and $MER = 18.95$ dB. The two nominal calculation passes are compared in Supplementary Data S06.

The small difference between the two calculation passes was intentionally retained rather than numerically merged. They agree within about 0.1% in target transmission and 0.3 dB in MER , providing an additional numerical consistency check of the nominal result.

The importance of this result extends beyond the magnitude of the extinction ratio. The target and the three competitors all belong to guided states of the same reference RCF and experience the same passive multilayer section. The structure therefore does not operate by blocking an externally defined spatial beam while transmitting another. Instead, selectivity arises from the distinct modal decomposition and phase evolution of the four guided input states within the same finite waveguide section.

The resulting guided-output powers of the target and competing reference-fiber modes are compared in Fig. 4.

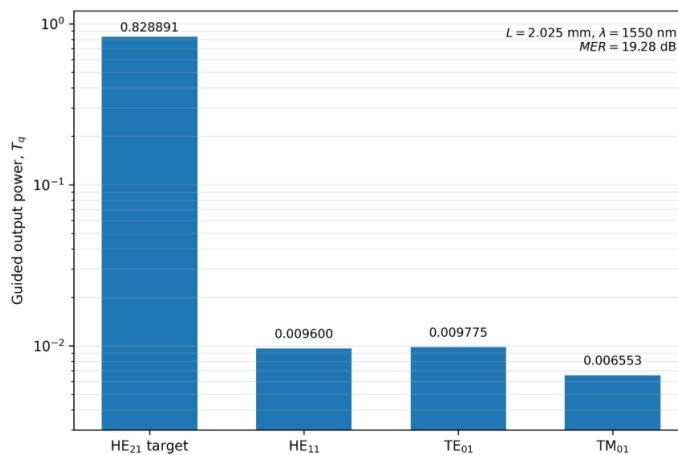


Fig. 4. Nominal guided-mode selectivity of the optimized five-layer ring-core section at $\lambda = 1550$ nm and $L = 2.025$ mm. The HE_{21} -based target family retains a guided output power of $T_{HE_{21}} = 0.828891$, whereas the competing HE_{11} , TE_{01} , and TM_{01} modes remain below 10^{-2} . The corresponding modal extinction ratio is $MER = 19.28$ dB.

5.2. Physical origin of the selectivity

The large difference between the target transmission and the transmissions of the competing modes cannot be explained simply by stronger confinement of the target field. At the first interface, each launched reference mode excites a set of guided eigenmodes of the multilayer section. These internal modal pathways have different propagation constants and therefore accumulate different phases before being projected back onto the corresponding guided state of the output reference fiber.

For a launched reference mode q , the contribution of an internal guided pathway p to the diagonal output channel $q \rightarrow q$ is written as

$$w_{qp}(L) = b_{qp} a_{qp} \exp(i\beta_p L), \quad (18)$$

where a_{qp} is the excitation amplitude of the p -th multilayer eigenmode at the input interface, b_{qp} is its projection amplitude onto the corresponding output reference mode, and β_p is its propagation constant. The total output amplitude is therefore

$$A_q(L) = \sum_p w_{qp}(L). \quad (19)$$

A convenient measure of the phase alignment of the participating pathways is the coherence factor

$$C_q(L) = \frac{|\sum_p w_{qp}(L)|}{\sum_p |w_{qp}(L)|}, \quad 0 \leq C_q \leq 1. \quad (20)$$

When C_q approaches unity, the dominant modal contributions are mutually phase-aligned and constructively reconstruct the corresponding output mode. In contrast, a small value of C_q indicates that appreciable internal modal amplitudes are present but largely cancel during coherent recombination.

Within the reciprocal forward bound-mode representation used for this diagnostic, the input and output reference-fiber sections are identical, and all modes are power-normalized. For the corresponding diagonal channel $q \rightarrow q$, the magnitudes of the reciprocal input and output overlap coefficients satisfy $|b_{qp}| = |a_{qp}|$.

We therefore define the bound-subspace coupling of the launched mode q as $B_q = \sum_p |a_{qp}|^2$. Using Eq. (18), the denominator of the coherence factor can then be written as

$$\sum_p |w_{qp}| = \sum_p |b_{qp} a_{qp}| = \sum_p |a_{qp}|^2 = B_q. \quad (21)$$

Since $T_q = |A_q|^2$, Eq. (20) may equivalently be evaluated as

$$C_q = \frac{|A_q|}{B_q} = \frac{\sqrt{T_q}}{B_q}. \quad (22)$$

Thus, B_q characterizes the coupling of the launched reference mode to the bound guided subspace of the multilayer section, whereas C_q characterizes how coherently these bound modal pathways recombine into the corresponding output reference mode. The complete final-design coherence diagnostic and bound-subspace coupling data are provided in Supplementary Data S05 and S09 and Supplementary Fig. S3.

For the final five-layer structure at $\lambda_0 = 1550$ nm and $L = 2.025$ mm, this analysis covered all four launched reference modes. The calculated absolute sums of the internal bound-path amplitudes, $\sum_p |w_{qp}|$, are approximately 0.939 for HE_{21} , 0.908 for HE_{11} , 0.940 for TE_{01} , and 0.936 for TM_{01} . Thus, all four launched modes couple appreciably to the bound guided modal subspace of the multilayer section; the competitors are not suppressed simply because they fail to enter the finite segment.

Using $T_q = |A_q|^2$, the resulting coherence factors are $C_{HE_{21}} = 0.970$, $C_{HE_{11}} = 0.108$, $C_{TE_{01}} = 0.105$, $C_{TM_{01}} = 0.086$. The corresponding target amplitude is $|A_{HE_{21}}| = 0.910$, very close to the total available bound-path amplitude of approximately 0.939. Hence, the HE_{21} -based target family undergoes predominantly constructive recombination. By contrast, the competing modes possess similarly large sums of internal path amplitudes but yield resultant amplitudes of only approximately 0.098 for HE_{11} , 0.099 for TE_{01} , and 0.081 for TM_{01} . Their low output transmissions therefore arise predominantly from destructive or weakly coherent recombination rather than from weak excitation of the multilayer section.

This result provides direct quantitative support for the interference mechanism proposed in Section 2. In particular, the low transmission of the competing channels is caused primarily by destructive or weakly coherent recombination rather than by weak coupling into the bound modal subspace.

The analysis also clarifies the role of higher radial modes inside the multilayer section. Their excitation is not necessarily detrimental. An intermediate higher-order radial eigenmode can serve as one of several coherent propagation pathways connecting the input and output reference states. Whether such a pathway contributes constructively or destructively depends on its excitation amplitude, propagation constant, accumulated phase, and output overlap. Modal multiplicity therefore provides an additional interference degree of freedom rather than representing only parasitic modal content. Discrimination therefore arises from mode-dependent coherent evolution in the finite multilayer section rather than from differential material attenuation.

5.3. Dependence on segment length

Because selectivity arises from relative modal phases, the physical length of the multilayer section is a critical parameter. Changing L changes all factors $\exp(i\beta_p L)$ simultaneously and therefore modifies the coherent sum in Eq. (19).

The numerical length scan shows a pronounced interference maximum around $L = 2.025$ mm, where high target transmission coincides with suppression of all three guided competitors. The useful length interval depends on the acceptable residual competitor level. For $T_t \geq 0.70$ and $T_{\text{worst}} \leq 0.01$, the contiguous interval is only $\Delta L \approx 0.275 \mu\text{m}$. Relaxing the competitor threshold to $T_{\text{worst}} \leq 0.02$ gives $\Delta L \approx 1.6125 \mu\text{m}$, while for $T_{\text{worst}} \leq 0.05$ the corresponding interval increases to $\Delta L \approx 4.125 \mu\text{m}$. These values demonstrate directly that the optimized response is phase-sensitive. The underlying local length scan and the corresponding contiguous tolerance intervals are provided in Supplementary Data S07–S08 and Supplementary Fig. S2. Fig. 5 shows the local dependence of the target and competing guided-mode transmissions on section length.

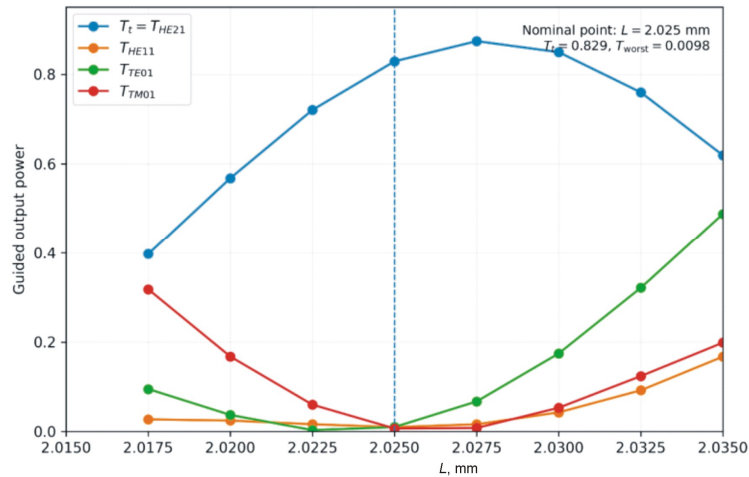


Fig. 5. Dependence of the guided output powers on the length of the finite multilayer section in a narrow interval around the nominal operating point $L = 2.025$ mm. The target transmission $T_t = T_{HE21}$ exhibits a pronounced local maximum near the selected length, while the competing HE_{11} , TE_{01} , and TM_{01} transmissions are simultaneously reduced. This confirms that the operating regime is governed by finite-length modal interference and that high selectivity is achieved only within a limited phase-matched length interval.

To examine whether the interference behavior persists over much longer distances, we evaluated an auxiliary reduced modal-beat continuation of the final short-length response over the 20–100 mm interval. This continuation is not an independent full-wave propagation calculation; it tests only the recurrence implied by the modal phase evolution. Its validation and representative recurrence results are provided in Supplementary Data S16–S18 and Supplementary Fig. S4.

The resulting modal transmissions exhibit recurrent rather than cumulative behavior. A relatively favorable recurrence occurs near $L = 63.454$ mm, where $T_t \approx 0.786$, $T_{worst} \approx 0.0215$, and $MER \approx 15.6$ dB. However, no sampled point in the 20–100 mm interval simultaneously satisfies the nominal criteria $T_t \geq 0.70$ and $T_{worst} \leq 0.02$, and the performance at the favourable recurrence remains inferior to that of the $L = 2.025$ mm operating point.

Therefore, longer propagation does not lead to cumulative modal purification; instead, the modal transmissions exhibit recurrent interference behavior. This auxiliary long-length analysis supports the physical interpretation of the device as a finite modal interferometer and confirms that the millimeter-scale optimum is not merely a truncation of a process that would continue to improve with length.

5.4. Waveguide/modal spectral response

The spectral behaviour was evaluated by repeating the full modal calculation at each wavelength. The eigenvalues, field distributions, propagation constants, and interface overlaps were therefore recalculated rather than obtained by simply scaling the phase of the 1550-nm solution.

Near the nominal wavelength, the target transmission remains high while the dominant competing mode changes with wavelength. For example, the full recalculation gives $T_t = 0.82966$ at 1550 nm, while $T_{HE_{11}} = 0.01056$, $T_{TE_{01}} = 0.00626$, $T_{TM_{01}} = 0.00966$. At this wavelength, $MER = 18.95$ dB.

The calculated waveguide/modal selectivity interval is defined by the simultaneous conditions $T_t \geq 0.70$ and $T_{\text{worst}} \leq 0.02$. Interpolating the wavelength sweep yields $1548.254\text{ nm} \leq \lambda \leq 1554.432\text{ nm}$, corresponding to an interval width of approximately $\Delta\lambda \approx 6.178\text{ nm}$. The complete wavelength-dependent modal response and interpolated operating-band limits are provided in Supplementary Data S10–S11. The spectral response of the target and competing guided-mode transmissions is shown in Fig. 6.

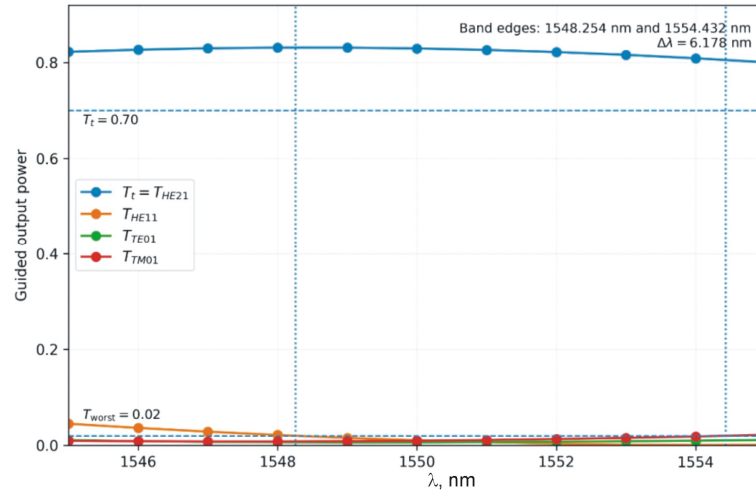


Fig. 6. Spectral dependence of the guided output powers for the target and competing modes of the optimized five-layer section. The curves show $T_t = T_{HE21}$ and the competing guided-mode transmissions T_{HE11} , T_{TE01} , and T_{TM01} as functions of wavelength. The horizontal dashed lines indicate the criteria $T_t = 0.70$ and $T_{\text{worst}} = 0.02$, while the vertical dotted lines mark the interpolated limits of the calculated waveguide/modal selectivity interval, 1548.254 nm and 1554.432 nm, obtained with the refractive indices n_H and n_L held constant. The corresponding interval width is approximately 6.178 nm.

The refractive indices n_H and n_L were held constant during the spectral sweep because the purpose of this calculation was to examine the wavelength-dependent modal and phase response of the finite-length selector while keeping the material parameters unchanged. The modal eigenvalues, field distributions, propagation constants, and interface overlaps were recalculated at each wavelength, so that the resulting variation reflects the waveguide and modal contributions to the spectral response.

5.5. Fabrication sensitivity and length re-trimming

The same interference mechanism that produces high modal selectivity also makes the structure sensitive to fabrication-induced changes in the optical path lengths. Variations in individual layer thicknesses or refractive indices modify both the eigenmode composition and the accumulated relative phases.

One-at-a-time perturbation tests show that this sensitivity is strongly parameter-dependent. At the nominal fixed length $L = 2.025\text{ mm}$, a thickness deviation of only $\Delta d_1 = \pm 10\text{ nm}$ can move the structure far from the nominal interference condition, reducing the target transmission and strongly increasing competing-mode reconstruction. Similar sensitivity is observed for $\Delta n_H = \pm 0.001$.

By contrast, the central layer d_3 and the inner radial position a are less destructive under the same absolute thickness perturbation. These results show that characterizing the structure with a single universal fabrication tolerance would be misleading.

A significant part of the degradation can, however, be recovered if the physical segment length is re-optimized after the radial perturbation. For example, after individual deviations of d_1, d_2, n_H , or n_L , adjustment of L restores target transmissions of approximately 0.75–0.84, with recovered MER values of approximately 14.2–18.4 dB. For instance, the perturbation $\Delta n_L = -0.001$ can be compensated by shifting the optimum length to approximately $L = 2.334$ mm, for which $T_t \approx 0.815$, $T_{\text{worst}} \approx 0.0118$, and $MER \approx 18.39$ dB. The complete one-at-a-time fixed-length perturbation set and the corresponding length re-trimming results are provided in Supplementary Data S12–S13. The effect of representative fabrication perturbations and the corresponding recovery achieved by re-trimming the segment length are summarized in Fig. 7.

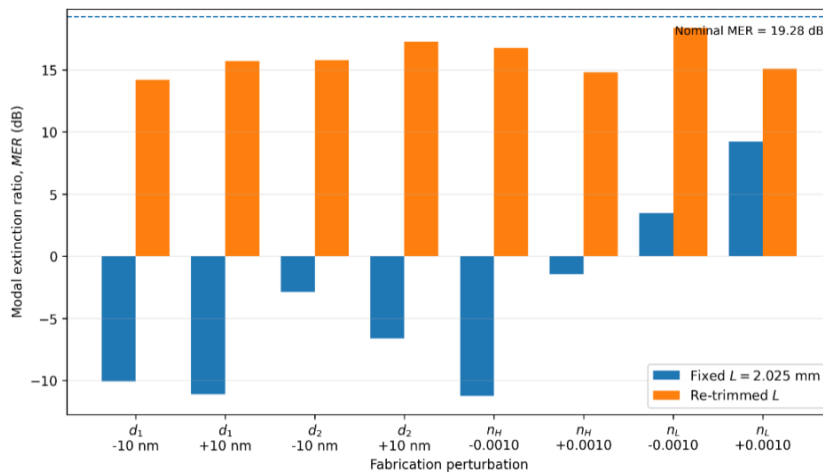


Fig. 7. Comparison of the modal extinction ratio MER for representative fabrication perturbations evaluated at the nominal fixed length $L = 2.025$ mm and after re-trimming the segment length. The blue bars correspond to the perturbed structures evaluated at the nominal length, whereas the orange bars show the recovered performance after re-optimizing L . In most cases, fabrication-induced degradation is largely due to detuning of the phase-matched interference condition rather than complete destruction of the modal-selection mechanism. The dashed horizontal line indicates the nominal unperturbed value $MER = 19.28$ dB.

The physical interpretation is important. A fabrication error does not necessarily destroy the modal-interference mechanism itself. In many cases, it mainly changes the propagation constants and therefore shifts the longitudinal position at which constructive target reconstruction and competitor cancellation occur. Re-trimming L cannot compensate for every possible geometrical error, because the error also changes modal overlaps, not just a common phase. Nevertheless, the recovery observed in the calculations confirms that a substantial fraction of the degradation is associated with detuning of the interference condition.

5.6. Model limitations and physical interpretation

The results above establish the feasibility of interference-based selection of a prescribed guided modal family within the stated model. They should not, however, be interpreted as a complete experimental demonstration of a finished fiber device.

First, the present work is theoretical and numerical. No dedicated fabrication or experimental transmission measurement of the proposed five-layer section has been performed. Second, the input state is a known guided mode of the reference RCF. Free-space generation, focusing, and coupling of an external vortex beam onto the fiber end face are outside the scope of

the present model. The calculated T_q values therefore characterize guided-mode transformation within the fiber system rather than free-space coupling efficiency. Third, the refractive-index profile is axisymmetric and reciprocal. It can select an OAM-compatible family characterized by $|l|$, but it does not distinguish the two signs $+l$ and $-l$. Selecting a definite handedness requires an additional symmetry-breaking mechanism, such as chirality, twist, anisotropy, or an azimuthally varying perturbation.

Fourth, radiation is treated using the open-guided approximation described in Section 3. Radiation components participate in interface matching but, once they leave the finite cladding, they are not allowed to return coherently from an artificial numerical boundary. The reported T_q values are therefore guided output powers, and the unaccounted guided power is not interpreted as material absorption. Fifth, the spectral calculation includes waveguide/modal dispersion but not the material dispersion of a specific realizable glass composition. A fabrication-oriented prediction over a wider wavelength interval would require experimentally justified Sellmeier functions for both high- and low-index materials. Sixth, the refractive-index values $n_H=1.520$ and $n_L=1.444$ are treated here as design parameters rather than as a model of a specific pair of fabricated glass compositions. The present calculations therefore establish the modal feasibility of the selected refractive-index profile, but do not by themselves demonstrate its realizability within a particular fiber-fabrication process. A fabrication-oriented design would also require accounting for material-specific dispersion, achievable index contrast, thermal compatibility, and processing constraints.

Finally, the fabrication-sensitivity analysis was restricted to one-at-a-time perturbations of selected layer thicknesses, refractive indices, and radial dimensions. We did not include correlated multi-parameter fabrication errors, ellipticity, concentricity errors, longitudinal nonuniformity, fiber bending, or interface roughness. The calculated 19-dB *MER* should therefore be interpreted as the performance of an optimized idealized geometry rather than as a guaranteed fabrication tolerance or manufacturing yield. Within the perturbations considered, re-trimming the physical segment length partially restores modal selectivity, indicating that much of the degradation arises from phase detuning; however, this compensation cannot generally correct changes in modal overlaps caused by arbitrary fabrication errors.

Within these limitations, the calculations support a more general physical conclusion. The radial multilayer profile does not merely define which eigenmodes can exist. Together with the finite propagation length, it provides a way to control how several guided vector eigenmodes interfere when they recombine into a prescribed output state. The mode-selective function therefore arises from combining radial modal engineering with finite-length coherent evolution.

6. Conclusions

A finite, longitudinally uniform multilayer ring-core section has been investigated as a passive selector of a prescribed guided modal family. The proposed structure does not rely on material absorption or active modulation. Its operation depends on exciting several guided eigenmodes of the multilayer section, their distinct phase accumulation over a finite propagation length, and their coherent recombination at the output interface. The full-vector Maxwell model confirms a selective operating regime for the HE_{21} -based OAM-compatible guided family. At the nominal wavelength of 1550 nm and the optimized length $L=2.025$ mm, the calculated target guided output power is approximately $T_i \approx 0.83$, while the strongest

competing guided mode remains near 0.01, corresponding to $MER \approx 19$ dB. Wavelength-dependent calculations with fixed refractive indices show that the selective regime persists over a finite interval of waveguide/modal selectivity. At the same time, partial recovery obtained by re-trimming the segment length indicates that fabrication-induced changes do not necessarily eliminate the interference mechanism but can shift its optimum operating condition. The results therefore show that radial multilayering can be used not only to modify the eigenmode spectrum of a ring-core waveguide but also as an interference design degree of freedom for finite-length guided-mode selection. In this interpretation, higher-order guided components inside the multilayer section are not necessarily parasitic; they can form coherent propagation pathways whose controlled phase evolution contributes to reconstructing the target state and suppressing competing states. This principle provides the physical basis for further development of compact passive guided-mode selectors.

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Author contributions. M.S.: Conceptualization, methodology, investigation, formal analysis, data curation, writing – original draft, visualization; C.Z., X.Z. - writing – review & editing

Ethics Statement. This study did not involve human participants, human data, or animal subjects, and therefore did not require ethical approval.

Data and Code Availability Statement. The Supplementary Materials include the finalized numerical datasets supporting the reported results, the final geometry configuration, supplementary validation figures, methodological notes, and a checkpoint notebook for loading the datasets and regenerating selected plots.

Supplementary Materials. The supplementary archive accompanying this article contains Supplementary Data S01–S20, Supplementary Figs. S1–S4, the final geometry configuration, methodological notes, and a checkpoint notebook to load the finalized datasets and regenerate selected validation plots.

References

1. Angelsky, O.V., Zenkova, C.Y., Hanson, S.G., Ivansky, D.I., Tkachuk, V.M., Zheng, J. (2021). Random object optical field diagnostics by using carbon nanoparticles, *Opt Express*, 29(2), 916–928.
2. Ramachandran, S., Kristensen, P., & Yan, M. F. (2013). Optical vortices in fiber. *Nanophotonics*, 2, 455–474.
3. Bozinovic, N., Yue, Y., Ren, Y., Tur, M., Kristensen, P., Huang, H., Willner, A. E., & Ramachandran, S. (2013). Terabit-scale orbital angular momentum mode division multiplexing in fibers. *Science*, 340, 1545–1548.
4. Brunet, C., Ung, B., Wang, L., Messaddeq, Y., LaRochelle, S., & Rusch, L. A. (2015). Design of a family of ring-core fibers for OAM transmission studies. *Optics Express*, 23, 10553–10563.
5. Zhu, G., Hu, Z., Wu, X., Du, C., Luo, W., Chen, Y., Cai, X., Liu, J., Zhu, J., & Yu, S. (2018). Scalable mode division multiplexed transmission over a 10-km ring-core fiber using high-order orbital angular momentum modes. *Optics Express*, 26, 594–604.
6. Feng, F., Jin, X., O'Brien, D., Payne, F., Jung, Y., Kang, Q., Barua, P., Sahu, J. K., Alam, S.-U., Richardson, D. J., & Wilkinson, T. D. (2017). All-optical mode-group multiplexed transmission over a graded-index ring-core fiber with single radial mode. *Optics Express*, 25, 13773–13781.
7. Tu, J., Lu, Q., Wang, Z., Gao, S., Liu, W., Yu, C., Li, Z., & Lu, C. (2021). Mode analysis of orbital angular momentum modes carrying multi-mode ring-core fibers. *Optics Communications*, 499, 127314.
8. Lu, Q., Tu, J., Wang, Z., Gao, S., Zhou, J., Xiao, Q., Shen, L., Lan, X., Liu, W., & Li, Z. (2022). Spin-orbit coupling suppressed high-capacity dual-step-index ring-core OAM fiber. *Optics Letters*, 47, 1141–1144.

9. Liu, Y., Wang, Y., Geng, W., Zhao, W., Zhang, H., Zhang, W., Pan, Z., & Yue, Y. (2023). Parabolic-index ring-core fiber supporting high-purity orbital angular momentum modes. *Sensors*, 23, 3641.
10. Bai, X., Chen, H., Zhuang, Y., & Cao, H. (2020). A new type Bragg fiber for supporting 50 orbital angular momentum modes. *Optik*, 219, 165153.
11. Sayed, R., Khaleque, A., Shaha, K. S. R., Kabir, M. A., & Aoni, R. A. (2025). Dual step-index ring core antiresonant fiber for broadband transmission of numerous OAM modes with high purity and quality. *Optical Materials Express*, 15, 379–394.
12. Zhou, J. (2015). OAM states generation/detection based on the multimode interference effect in a ring core fiber. *Optics Express*, 23(8), 10247–10258.
13. Wu, G., Wu, X., Gao, S., Tu, J., Zhou, J., Sui, Q., Liu, W., & Li, Z. (2022). Multi-channel higher-order OAM generation and switching based on a mode selective interferometer. *Optics Express*, 30(14), 25093–25102.
14. Tsao, C. Y. H., Payne, D. N., & Gambling, W. A. (1989). Modal characteristics of three-layered optical fiber waveguides: A modified approach. *Journal of the Optical Society of America A*, 6, 555–563.
15. Brunet, C., Ung, B., Bélanger, P.-A., Messaddeq, Y., LaRochelle, S., & Rusch, L. A. (2014). Vector mode analysis of ring-core fibers: Design tools for spatial division multiplexing. *Journal of Lightwave Technology*, 32, 4046–4057.
16. Brunet, C., Bélanger, P.-A., & Rusch, L. A. (2016). Exact expressions for vector mode cutoff in three-layer step-index fibers. *Journal of Lightwave Technology*, 34, 3094–3102.
17. Snyder, A. W., & Love, J. D. (1983). *Optical Waveguide Theory*. Chapman and Hall, London.
18. Strynadko, M. (2026). Vector modes of a ring-core optical fiber: A Maxwell-based tutorial derivation with physical interpretation. *Preprints*.

Strynadko, M., Zenkova, C., & Zhang, X. (2026). Interference-Based Modal Selection in a Finite Multilayer Ring-Core Waveguide. *Ukrainian Journal of Physical Optics*, 27(5), S1017 – S1037.
doi: 0.3116/16091833/Ukr.J.Phys.Opt.2026.S1017

Анотація. Запропоновано скінченний поздовжньо однорідний багатошаровий кільцево-серцевинний сегмент для пасивної селекції заданого сімейства спрямований мод. Фізичний механізм селекції ґрунтується на розкладанні вхідної моди за власними модами багатошарової ділянки, накопиченні ними різних фаз на скінченній довжині та когерентній рекомбінації на вихідній межі. Для аналізу використано повновекторну модель на основі рівнянь Максвелла, узгодження мод на межах та врахування радіаційних компонент у моделі відкритого хвильоводу. Для оптимізованої п'ятишарової структури H-L-H-L-H при довжині хвилі 1550 нм отримано потужність цільового HE_{21} -сумісного з орбітальним моментом імпульсу сімейства близько 0,83, тоді як передавання конкурентних HE_{11} , TE_{01} і TM_{01} мод становить близько 0,01 або менше. Відповідне модове відношення екстинкції становить приблизно 19 дБ. Розрахований інтервал хвильоводно-модової селективності охоплює приблизно 1548,25–1554,43 нм за фіксованих показників заломлення. Аналіз технологічних відхилень показує високу фазову чутливість структури, однак повторне підстроювання довжини сегмента частково відновлює модову селективність. Отримані результати показують, що радіальне багатошарове структурування може використовуватися як інтерференційний ступінь свободи для селекції спрямований мод у скінченних волоконних сегментах.

Ключові слова: кільцево-серцевинне оптоволокно, орбітальний момент імпульсу, багатошаровий хвильовід, модова інтерференція, модова селекція