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Dispersion Slope Matching and Polarization Control in Photonic Crystal Fibers: Hybrid Design Strategies for the Next Optical Era

Amit Halder[1]* & Sumet Innas Mugdho[2]

[1]*Assistant Professor, Department of Electrical and Electronic Engineering, World University of Bangladesh, Dhaka-1230, Bangladesh.* [2]*BAF Shaheen College, Dhaka-1206, Bangladesh. Corresponding Author Email: amit.rueten@gmail.com**

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ABSTRACT

Photonic crystal fibers (PCFs) have emerged as foundational components in advanced optical communication, nonlinear signal processing, and precision sensing. Achieving simultaneous control of relative dispersion slope (RDS) and birefringence remains a key challenge, particularly in hybrid-core and multi-material PCFs designed for dense wavelength division multiplexing (DWDM) systems. This review consolidates recent advances in dispersion and polarization management, emphasizing the coupling between geometric structuring and material engineering. The mathematical framework of RDS matching is analyzed alongside a comparison of index-guiding and photonic-bandgap mechanisms. Hybrid architectures—spanning silica–polymer to chalcogenide–tellurite combinations—are examined for their capacity to enhance birefringence and nonlinear response. Emerging directions, including metamaterial inclusions, nanowire-assisted cores, and AI-driven inverse design, are discussed in the context of bridging the simulation–fabrication divide. The review concludes by outlining research priorities for experimentally validated, dispersion-engineered, and polarization-controlled hybrid PCFs, paving the way for scalable, high-performance photonic systems.

Keywords: Photonic Crystal Fibers; Hybrid-Core Fibers; Dispersion Engineering; Relative Dispersion Slope Matching; Birefringence Control; Dense Wavelength Division Multiplexing (DWDM); Polarization Management; Hybrid Materials; Photonic Bandgap Fibers; Nonlinear Optics; Inverse Design; Optical Fiber Sensors.

1. Introduction

High-speed optical communication and photonic signal processing have pushed fiber technologies to unprecedented performance levels [1]. Dense wavelength division multiplexing (DWDM) systems, in particular, require finely engineered dispersion profiles to minimize pulse broadening and inter-channel crosstalk [2]. Conventional dispersion-compensating fibers suffer from inherent limitations, including restricted design flexibility, high insertion loss, and weak control over higher-order dispersion.

Photonic crystal fibers (PCFs), with their structural tunability and material versatility, offer a powerful platform for achieving dispersion slope matching and polarization control in next-generation optical networks [3]. Dispersion slope matching—typically expressed through the relative dispersion slope (RDS)—ensures that a compensating fiber maintains a dispersion profile parallel to that of standard single-mode fibers across C- and L-band wavelengths [4]. This alignment minimizes differential group delay across DWDM channels, preserving signal integrity near 1.55 μm.

Simultaneously, managing birefringence is essential for maintaining stable polarization states and ensuring robust performance in the presence of thermal and mechanical perturbations. Achieving both optimized RDS and strong birefringence in a single PCF design is technically demanding because the structural or material adjustments that improve one parameter often perturb the other [5].

Hybrid PCFs, which integrate multiple materials or combine different guiding mechanisms (such as index guiding and photonic bandgap effects), introduce new degrees of freedom to this coupled design problem [6]. Recent progress in polymer–glass and chalcogenide–silica combinations, along with advances in extrusion and hybridized stack-and-draw fabrication, has enabled more realistic pathways toward broadband dispersion control and stable polarization management [7]. Hybrid photonic crystal fibers address these limitations by combining geometric asymmetry with material contrast [8], enabling simultaneous tuning of dispersion slope [9], birefringence [10], and nonlinearity beyond what is achievable with single-material PCFs [11]. The use of multi-material cores and selective inclusions provides additional degrees of freedom that are particularly effective for DWDM-compatible dispersion and polarization control.

Figure 1 illustrates the structure of a photonic crystal fiber (PCF) consisting of a solid silica core surrounded by a periodic array of air holes forming the cladding. The geometric parameters pitch (Λ) and hole diameter (d) govern the fiber's dispersion and confinement properties.

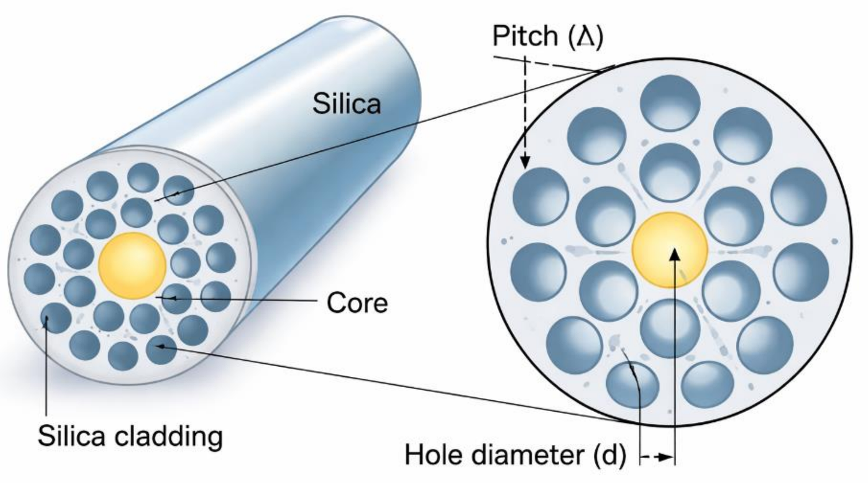

Figure 1. Schematic of a photonic crystal fiber showing the solid core, air-hole cladding, pitch (λ), and hole diameter (d).

Despite these advances, most hybrid PCF designs remain confined to numerical studies, with experimental demonstrations lagging behind. Fabrication-induced asymmetries, interfacial stresses, and material compatibility challenges continue to limit practical implementation. Furthermore, the interplay between material and geometric dispersion in hybrid structures remains insufficiently understood.

This review examines the theoretical foundations of dispersion slope matching and birefringence control in hybrid PCFs, outlines major developments, highlights fabrication challenges, and identifies open research gaps that must be addressed to realize practical hybrid PCF technologies.

1.1. Study objectives

The specific objectives of this study are:

- To systematically review dispersion slope matching theory in photonic crystal fibres and its relevance to DWDM-compatible dispersion compensation.
- To critically analyse the coupled relationship between relative dispersion slope (RDS) and birefringence, highlighting the inherent trade-offs in conventional single-material PCFs.

- To evaluate how hybrid-core and multi-material PCF architectures enable independent and simultaneous control of dispersion slope, birefringence, and nonlinearity.

- To compare index-guiding and photonic-bandgap mechanisms in the context of dispersion engineering and polarization control.

- To survey fabrication techniques and experimental challenges associated with hybrid PCFs, identifying key causes of performance degradation relative to numerical predictions.

- To identify emerging design trends—including metamaterial-assisted structures, nanowire inclusions, and AI-driven inverse design—and outline future research directions toward experimentally realizable, high-performance hybrid PCFs.

2. Theoretical Background

2.1. Dispersion

Total chromatic dispersion $D(\lambda)$of an optical fiber is the sum of material dispersion and waveguide dispersion [8]:

$$D(\lambda) = D_{\mathrm{m}}(\lambda) + D_{\mathrm{w}}(\lambda) \tag{1}$$

where $D_m(\lambda)$originates from the intrinsic wavelength dependence of the refractive index of the fiber material, while $D_w(\lambda)$arises from the fiber's geometrical structure and modal confinement, enabling dispersion tailoring through PCF design parameters.

In terms of the wavelength-dependent effective refractive index, the total dispersion is given by [9]:

$$D(\lambda) = -\frac{\lambda}{c}\,\frac{d^2\,\mathrm{Re}[n_{\mathrm{eff}}]}{d\lambda^2} \tag{2}$$

where $\mathrm{Re}[n_{\mathrm{eff}}]$denotes the real part of the modal effective refractive index and $c$is the speed of light in vacuum; this expression highlights that chromatic dispersion in optical fibres is governed by the curvature of the effective index spectrum, which can be engineered through geometry and material selection.

Material dispersion D_{m} arises from the intrinsic wavelength dependence of the refractive index of the base material. Waveguide dispersion D_{w} is governed by the fiber geometry—specifically the air-hole diameter d, pitch Λ, and air-filling fraction $\frac{d}{\Lambda}$.

Figure 2 illustrates the chromatic dispersion in optical fibre communication.

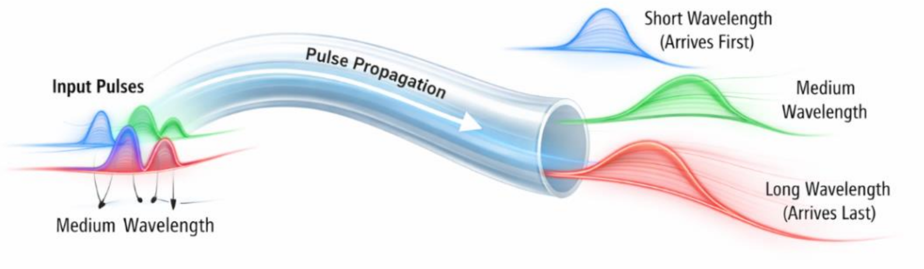

Figure 2. Chromatic dispersion in optical fibre.

Because PCFs allow geometry and material properties to be independently tuned, they enable dispersion tailoring from the visible regime to the mid-infrared—capabilities unattainable in conventional step-index fibers.

2.2. Relative dispersion slope (RDS)

In dense wavelength-division multiplexing (DWDM) systems, dispersion compensation requires both fibers to maintain parallel dispersion curves across the operating spectrum. This condition is expressed by the Relative Dispersion Slope (RDS) [10]:

$$\mathrm{RDS}(\lambda) = \frac{\frac{dD(\lambda)}{d\lambda}}{D(\lambda)} \tag{3}$$

where the RDS(λ) quantifies the wavelength scaling of chromatic dispersion D(λ); matching the RDS of a compensating fiber to that of standard single-mode fiber ensures uniform dispersion compensation across all DWDM channels, minimizing differential group delay.

When two fibers exhibit equal RDS values, their dispersion characteristics scale proportionally with wavelength, ensuring consistent pulse broadening compensation across all channels.

For compatibility with standard SMF-28 at 1550 nm, a dispersion-compensating or hybrid PCF must achieve RDS to 0.0034 nm^{-1} at λ=1.55 µm [11].

Achieving this requires simultaneous tuning of: core–cladding refractive-index contrast, air-hole geometry and pitch, and intrinsic material dispersion of the chosen polymer or glass.

Hybrid PCFs offer additional flexibility by introducing material combinations that modify slope behavior without severely perturbing single-mode guidance.

2.3. Birefringence and polarization control

Birefringence in PCFs occurs when the two orthogonal polarization modes experience different effective refractive indices [12]:

$$\Delta n = | n_x - n_y | \tag{4}$$

where $n_x$and $n_y$are the effective refractive indices of the two orthogonal polarization modes; a larger Δnindicates stronger polarization anisotropy, enabling improved polarization maintenance and reduced cross-polarization coupling.

The corresponding beat length, which quantifies the coupling strength between the polarization axes, is [13]:

$$L_b = \frac{\lambda}{\Delta n} \tag{5}$$

where L_b represents the propagation length over which the two polarization modes accumulate a 2π phase difference; a shorter beat length corresponds to stronger birefringence and enhanced polarization stability in practical fiber applications.

A shorter beat length indicates stronger birefringence and more robust polarization maintenance.

High birefringence in PCFs is typically achieved through:

1) Geometric asymmetry: Elliptical or enlarged air holes, Off-center or asymmetric core formation.

2) Stress-applying elements (SAEs): Doped silica rods, Polymer–glass hybrid inclusions that induce anisotropic strain.

3) Hybrid-material engineering: Combinations of materials with differing thermo-optic coefficients, thermal expansion coefficients, or elastic moduli. However, increasing birefringence often perturbs the dispersion profile, leading to a well-known birefringence–dispersion trade-off.

Hybrid PCFs mitigate this issue by distributing anisotropy across material interfaces, allowing birefringence enhancement while maintaining controlled dispersion.

2.4. RDS-birefringence interrelation and multi-objective optimization

In photonic crystal fibers designed for relative dispersion slope (RDS) matching, optimization is inherently multi-objective because dispersion compensation performance and polarization control must be achieved simultaneously for practical DWDM applications. RDS matching requires that the dispersion curve of the compensating PCF remains parallel to that of standard single-mode fiber across the operating wavelength band, while birefringence must be sufficiently high to maintain polarization stability under environmental perturbations.

These objectives are physically coupled. Structural modifications intended to enhance birefringence—such as core asymmetry, selective air-hole enlargement, or anisotropic material inclusion—alter modal confinement and effective refractive index dispersion, which can shift the zero-dispersion wavelength (ZDW) and modify the dispersion slope. Conversely, design adjustments aimed at precise RDS matching, including tuning of pitch, air-filling fraction, or refractive-index contrast, often reduce polarization anisotropy and weaken birefringence.

As a result, RDS-matched PCF design cannot rely on independent tuning of dispersion and polarization parameters. Instead, dispersion and birefringence must be treated as concurrently constrained performance metrics, evaluated across the same structural and material parameter space. Numerical modeling using wavelength-resolved modal analysis—typically based on the finite element method (FEM) or beam propagation method (BPM)—is therefore essential to assess how changes in geometry or material composition affect both dispersion slope and polarization behavior simultaneously [14].

Hybrid photonic crystal fibers provide a more favorable optimization landscape by allowing partial decoupling of waveguide and material dispersion contributions while distributing anisotropy across multiple interfaces. This enables RDS matching to be preserved while achieving practically useful birefringence levels, forming the physical basis for hybrid PCFs as viable dispersion-compensating and polarization-controlling fibers in DWDM systems.

3. Evolution of dispersion and polarization management in PCF

The evolution of photonic crystal fiber (PCF) design for dispersion and polarization control has progressed through four interconnected phases, each driven by emerging system-level requirements in optical communication and photonics.

3.1. Early dispersion-engineered PCFs (2000–2010)

The first decade emphasized flattening dispersion rather than slope matching. Triangular and hexagonal lattice PCFs achieved ultra-flattened dispersion (<±1 ps/nm·km) over 1.2–1.7 μm with tailorable ZDW [15]-[18]. However, these designs exhibited low birefringence (10^{-6}–10^{-5}), high confinement loss at long wavelengths, and ignored higher-order effects like dispersion slope—parameters crucial for advancing DWDM [19]-[21].

3.2. Transition to RDS matching (2010–2015)

As DWDM expanded across C- and L-bands, dispersion slope matching emerged as vital. The RDS concept guided development of dispersion-compensating PCFs (DC-PCFs) matching SMF-28 slope. Innovations included dual-core PCFs, asymmetric air-hole arrangements, and selective doping. Yet birefringence remained modest (10^{-5}–10^{-6}) in silica-based designs [22].

3.3. Birefringence integration (2015–2020)

With polarization-division multiplexing (PDM) and coherent systems, polarization co-engineering became essential. Key innovations included elliptical-core PCFs achieving Δn to 10^{-3}, asymmetric hole lattices, and stress-applying elements [23]. This era produced highly birefringent dispersion-compensating PCFs (HB-DC-PCFs) with both RDS matching and polarization maintenance [24]-[25]. However, designs remained predominantly numerical; experimental realizations suffered from hole diameter uniformity, core ellipticity errors, and unpredictable stress profiles.

3.4. Emergence of hybrid PCFs (2020–present)

Limitations of single-material PCFs motivated hybrid architectures. Examples include silica–polymer hybrids (low-cost, tunable dispersion), silica–tellurite/chalcogenide hybrids (high nonlinearity), and Zeonex-based polymer PCFs (thermal stability) [26]-[28]. Hybridization allows independent control of material and waveguide dispersion. Recent advances in extrusion, 3D-printed preforms, and stack-and-draw integration made hybrid PCFs increasingly feasible. Computational optimization via machine learning and adjoint inverse design accelerated parameter tuning.

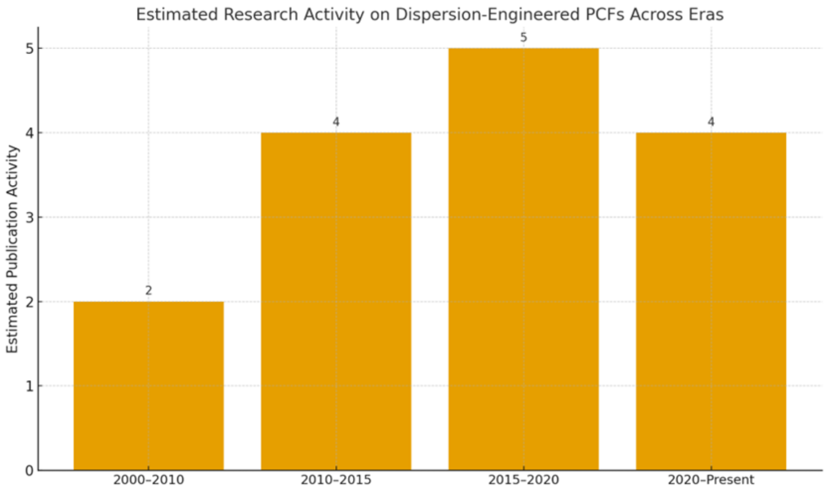

Figure 3. Estimated research activity on dispersion-engineered photonic crystal fibres across four developmental eras, based on relative bibliometric trends.

Figure 3 summarizes the approximate evolution of research activity in dispersion-engineered PCFs. Early work (2000–2010) shows comparatively low output, reflecting the foundational phase of dispersion-flattened PCF development. Activity increases markedly during 2010–2015, coinciding with the rise of residual dispersion slope (RDS) matching for DWDM systems. The 2015–2020 period exhibits the highest activity, driven by advances in birefringent, polarization-maintaining, and coherent-system-compatible PCFs. Research from 2020 onward remains strong, with emphasis shifting toward hybrid-material structures, polymer–glass architectures, advanced fabrication methods, and computationally optimized designs.

4. Birefringence Control in Hybrid PCFs

4.1. Birefringence mechanisms

Form Birefringence stems from geometric asymmetry. Strategies include elliptical cores and asymmetric air-hole lattices. Strength depends on index contrast and asymmetric degree.

Stress-Induced Birefringence exploits differential thermal contraction via photo elastic effects, inspired by "PANDA" and "Bow-Tie" PM fibers [29]. PCF extensions include stress-applying rod embedding and hybrid thermal mismatch exploitation. Stress birefringence depends on fabrication precision and post-draw cooling.

Hybrid Multi-Mechanism Birefringence combines form and stress effects. Silica–polymer cores create interfacial stress while maintaining structural asymmetry. Hybridization introduces anisotropic material properties, enabling temperature-tunable birefringence [30].

Table 1 depicts how form, stress, and hybrid-induced birefringence differ in origin, mechanism, and control approach. It illustrates that form birefringence arises from structural geometry, stress birefringence from mechanical forces, and hybrid-induced birefringence from their combination, highlighting how each type enables different optical applications.

Table 1. Comparison of form, stress, and hybrid-induced birefringence and their key characteristics

Type	Origin	Key Mechanism	Typical Materials/ Structures	Control Method	Applications
Form Birefringence	Structural anisotropy (sub wavelength patterns, layered media)	Different refractive indices along structured axes due to geometry	Nanostructured gratings, photonic crystals, multilayer films	Change geometry, fill factor, or periodicity	Polarizers, waveplates, metasurfaces
Stress Birefringence	Internal or external mechanical stress	Stress alters molecular orientation changes refractive index	Glass, polymers, optical fibers	Apply mechanical load or thermal gradients	Stress analysis, tunable optics, fiber sensors
Hybrid-Induced Birefringence	Combination of form and stress effects	Stress amplifies or modifies structural birefringence	Polymer composites, liquid crystal elastomers, nanostructured films	Combine micro structuring + stress or strain	Adaptive optics, tunable photonics

4.2. Geometry and lattice symmetry effects

PCFs uniquely tune birefringence without sacrificing single-mode operation, confining modes within central defects to reduce cross-axis coupling despite asymmetry [31].

4.3. Birefringence–dispersion trade-off and mitigation

Enhancing birefringence distorts mode fields and shifts ZDW. In hybrid photonic crystal fibres, this interdependence can be partially decoupled. High-Δn materials (chalcogenides) maintain slope stability [32].

4.4. Experimental characterization and fabrication challenges

Characterization techniques such as interferometric phase-shift measurements, polarization beat-length analysis, and Sagnac loop interferometry are widely used to quantify birefringence and structural stability in PCFs [33]. However, thermal expansion mismatches between materials can lead to gradual birefringence drift, complicating long-term performance. Fabrication itself introduces additional challenges, including air-hole deformation, asymmetric collapse during drawing, and microvoid formation, all of which degrade optical properties. As a result, experimentally achieved performance often falls 30–50% short of theoretical predictions [34]. To address these gaps, emerging approaches such as pressure-assisted drawing and real-time OCT-based monitoring are being adopted to improve structural fidelity and process control.

5. Index-Guiding vs. Photonic-Bandgap PCFs

5.1. Index-guiding PCFs

Index-guiding PCFs confine light through total internal reflection. This mechanism offers design flexibility for dispersion engineering. Index-guiding PCFs dominate current applications [35].

5.2. Photonic-bandgap PCFs

PBG fibers confine light in bandgap regions. They offer reduced nonlinearity, endlessly single-mode operation, and low chromatic dispersion. Still, they suffer from higher confinement loss and narrower transmission windows [36].

5.3. Hybrid implementations

Recent hybrid designs combine index-guiding and PBG mechanisms, exploiting advantages of both.

6. Hybrid Material Architectures

6.1. Material selection principles

Key material combinations used in hybrid PCFs include silica–polymer structures, silica paired with chalcogenide or tellurite glasses, and silica–fluoride hybrids, each selected to balance optical performance, thermal behavior, and fabrication compatibility.

6.2. Fabrication techniques

A. Stack-and-Draw Method: Allows precise placement of different materials but carries risks such as interface delamination during drawing [37].

B. Extrusion-Based Fabrication: Provides excellent material intermixing and is suitable for complex hybrids, though it requires carefully designed mold geometries [38].

C. 3D Preform Printing: Offers high design freedom and supports intricate structures that are otherwise difficult to fabricate [39].

D. Capillary Stacking: Commonly used for prototypes and research fibers but is labor-intensive and less scalable [40].

6.3. Interfacial effects and stress management

Thermal expansion mismatches between materials generate residual stresses that affect birefringence and long-term stability [41]. Finite-element thermo-mechanical modeling is often used to predict stress distributions, while controlled annealing protocols help relax and minimize these stresses.

7. Emerging Frontiers

7.1. Metamaterial-assisted PCFs

Incorporating metamaterial elements allows exceptional dispersion control, with structures like split-ring resonators tailoring the local effective index [42]. However, practical fabrication of these complex inclusions remains a significant challenge.

7.2. Nanowire-embedded PCFs

Embedding metal nanowires enables strong plasmonic coupling, opening pathways for enhanced nonlinear interactions and highly sensitive sensing applications [43].

7.3. AI-driven inverse design

Machine learning is rapidly transforming PCF design, with genetic algorithms exploring vast design spaces, neural networks providing instant performance predictions, and adjoint-based topology optimization delivering efficient, high-resolution structural refinement [44].

7.4. Reconfigurable hybrid PCFs

Hybrid fibers incorporating liquid crystals offer tunable birefringence, enabling dynamically reconfigurable components such as next-generation DWDM systems [45]. A hybrid photonic crystal fiber incorporating high-index chalcogenide glass nanolayers inside the air holes show thermally tunable transmission resonances. By adjusting temperature, the resonant band edges shift significantly (e.g., ~3.6 nm/°C sensitivity at ~1300 nm), offering a reconfigurable spectral response in the hybrid PCF platform [46]. A polymer photonic crystal fiber with integrated chalcogenide As_2S_3 nanofilms exhibits nonlinear reconfigurability—intensity-dependent shifts in transmission band edges (up to ~17 nm) due to the ultra-high Kerr nonlinearity of the hybrid materials [47]. These examples demonstrate how hybridization of materials in PCFs (e.g., combining polymers and high-index glasses) enables reconfigurable optical characteristics through external stimuli like temperature or optical intensity—key advances in tunable fiber platforms.

8. Numerical modeling and simulation

A range of computational tools underpin modern fiber and waveguide analysis, each serving a distinct role. The Finite Element Method (FEM) remains the gold standard for accurate modal calculations, particularly when dealing with intricate or highly asymmetric geometries [48]. For propagation-focused studies, the Beam Propagation Method (BPM) excels in modeling nonlinear dynamics and mode coupling along the fiber length. When full electromagnetic rigor is required, full-wave solvers such as FDTD and Fourier modal methods provide comprehensive field solutions, making them especially valuable for photonic bandgap structures. Complementing these numerical approaches, coupled-mode theory offers a simplified analytical framework that is highly effective for perturbation studies and gaining rapid physical insight without heavy computation [49]-[50]. Figure 4 illustrates the conceptual relationships among commonly used numerical modeling techniques in photonic waveguide analysis. Full-wave solvers such as the finite element method (FEM) and finite-difference time-domain (FDTD) directly solve Maxwell's equations, providing rigorous electromagnetic field solutions. Reduced-order approaches, including coupled-mode theory (CMT) and the beam propagation method (BPM), are derived under specific assumptions and often rely on parameters extracted from full-wave simulations. The figure highlights how these methods complement each other in balancing physical accuracy, computational efficiency, and analytical insight.

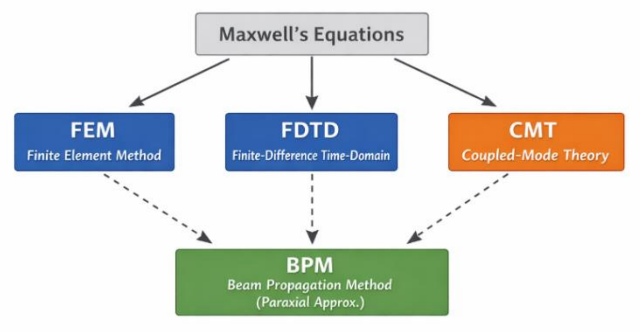

Figure 4. Conceptual relationship between commonly used numerical modelling techniques in photonic waveguide analysis.

9. Simulation–fabrication gap: challenges and solutions

Deviations between designed and realized fibre performance often stem from several intertwined factors. Geometric tolerances—such as fluctuations in air-hole diameter and pitch—can significantly shift the intended relative dispersion slope, while interfacial issues like imperfect bonding or surface roughness introduce additional confinement loss and scattering. Material properties also drift from specifications, with real-world dispersion and absorption affected by contamination or processing history. Even carefully engineered stress-induced birefringence can partially relax during fabrication, reducing the expected polarization control.

To close these gaps, several strategies are proving effective: integrating optical FEM with thermo-mechanical solvers to capture coupled behaviors, implementing real-time process control through in-situ OCT and acoustic monitoring, and embracing statistical design methods such as tolerance analysis and Monte Carlo simulations. Rapid prototyping using 3D-printed preforms and controlled extrusion further accelerates optimization, while precise material characterization ensures that models align with actual fabrication conditions.

In summary, bridging the simulation–fabrication gap primarily depends on overcoming three key barriers—geometric deviations, interfacial imperfections, and material property variations—which collectively determine how closely the fabricated fibre matches its designed performance.

░10. Applications

These advances open significant opportunities across multiple photonics domains. In optical communication, matched relative dispersion slopes enable effective DWDM compensation over longer spans, while stable polarization performance boosts coherent receiver efficiency and supports high-capacity PDM formats in 100G+ systems [51]. In nonlinear photonics, flattened dispersion profiles facilitate efficient four-wave mixing for broadband supercontinuum generation, with hybrid-core structures further improving conversion bandwidth [52]. Engineered dispersion also drives high-gain parametric amplification, expanding the toolbox for on-chip and fiber-based nonlinear devices [53]. In precision sensing, stable birefringence greatly enhances interferometric sensor reliability, and temperature-tunable PCFs provide flexible, reconfigurable sensing platforms [54]. Low-loss hybrid fibers additionally support long-distance distributed sensing. Emerging applications continue to benefit as well: chalcogenide PCFs enable mid-infrared spectroscopy beyond 20 μm, unlocking new capabilities in biomedical diagnostics, while dispersion-engineered fibers support quantum light generation for next-generation quantum optics [55].

░11. Critical Research Gaps and Future Directions

11.1. Identified Gaps

a) Theory–Experiment Gap: Experimental results often lag predictions by 30–50%, with limited systematic validation.

b) Scalability Issues: Most designs remain lab-scale; industrial fabrication still lacks standardized, reproducible processes.

c) Material Limitations: Long-term material compatibility and stability remain insufficiently characterized.

d) Birefringence Drift: The underlying mechanisms of long-term birefringence instability are still poorly understood.

e) Interface Losses: Optical loss at multi-material interfaces is not yet accurately modeled.

f) ML Overfitting: Current models often rely heavily on synthetic or simulation-based data, which can cause overfitting and limit real-world applicability. Incorporating larger, experimentally validated datasets is essential to improve model generalization and ensure predictions remain robust under practical fabrication and environmental conditions.

g) Multiphysics Integration: Many existing simulation frameworks fail to fully couple optical, thermal, and mechanical effects, leading to incomplete understanding of performance under varying fabrication stresses and operating conditions. Enhanced multiphysics modeling is needed to capture these interdependencies accurately.

h) Process Monitoring Limitations: Real-time monitoring tools, such as in-situ OCT and acoustic sensing, remain underutilized and insufficiently integrated with control systems. More adaptive, closed-loop feedback mechanisms are required to maintain consistency during high-precision fiber fabrication.

i) Standardization and Reproducibility: A persistent challenge across photonic fiber research is the lack of standardized fabrication protocols and characterization benchmarks. Variations in preform fabrication methods, measurement techniques, and data reporting practices make it difficult to compare results across studies or validate simulation outcomes. Establishing shared reference materials, open-access process parameters, and common data formats would significantly enhance reproducibility and accelerate cross-laboratory validation. Developing standardized testing procedures for dispersion, loss, and birefringence would also help ensure that performance metrics are both consistent and comparable across platforms.

11.2. Recommended Pathways

a) Integrated Frameworks: Develop unified models that couple optical design with thermo-mechanical behaviour to improve predictive accuracy and reduce fabrication uncertainty.

b) Advanced Control: Implement in-situ monitoring and feedback systems capable of achieving sub-percent fabrication tolerances for higher repeatability.

c) Material Science Progress: Create new bridging materials with superior thermal, mechanical, and chemical stability to enhance long-term device performance.

d) Long-Term Characterization: Conduct systematic studies on birefringence drift and other aging effects to understand and mitigate long-term degradation.

e) Robust Optimization: Use uncertainty-quantification frameworks to design and optimize systems that remain stable under real-world variability.

f) Cross-Disciplinary Collaboration: Foster teams combining optical engineers, materials scientists, and fabrication specialists to accelerate innovation and solve complex challenges holistically.

12. Conclusion

Hybrid photonic crystal fibers (PCFs) now represent a mature platform where geometric, material, and photonic-bandgap design converge to enable precise dispersion and polarization control. However, persistent discrepancies between simulated and fabricated performance highlight the need for integrated modeling–fabrication workflows, real-time process monitoring, and machine learning trained on experimental datasets. Continued advances in extrusion, 3D preform printing, and in-situ diagnostics are rapidly narrowing this gap, positioning hybrid PCFs as key enablers of next-generation optical networks, supercontinuum generation, and precision photonic sensing. Looking forward, several research directions merit attention: developing comprehensive multiphysics models that couple optical, thermal, and mechanical phenomena; establishing standardized fabrication and characterization protocols to enhance reproducibility; creating large, experimentally validated datasets for AI-driven design; exploring new hybrid material combinations with improved thermal and nonlinear properties; integrating adaptive process control for dynamic compensation of fabrication errors; and advancing scalable, low-loss manufacturing routes for multi-material preforms. Collectively, these efforts will accelerate the realization of practical, high-performance hybrid PCFs capable of meeting the demands of emerging photonic technologies.

Declarations

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Competing Interests Statement

The authors declare that they have no competing interests related to this work.

Consent for publication

The authors declare that they consented to the publication of this study.

Authors' contributions

Both the authors took part in literature review, analysis, and manuscript writing equally.

Availability of data and materials

Supplementary information is available from the authors upon reasonable request.

Institutional Review Board Statement

Not applicable for this study.

Informed Consent

Not applicable for this study.

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