



Full-wave and machine-learning modelling of cylindrical fiber Bragg gratings



İSTANBUL
OKAN ÜNİVERSİTESİ

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1. Cylindrical geometry, materials and the structure

Abstract

A fiber Bragg grating reflects one narrow band of wavelengths and passes the rest. Designers predict this with a simple model assuming light stays guided everywhere along the grating. Strong index contrast breaks the assumption. So do deep low-index slots. Light escapes sideways while crossing a slot, and the dip you measure reports leakage, not reflection. We solve Maxwell equations for the full cylindrical geometry and drop the weak-index assumption. One calculation follows a broadband pulse through two hundred periods of a 530 nm grating. A second computes the allowed frequencies of one repeated period. Both place the reflection band near 1535 nm and agree to better than one percent. The finite grating length sets this residual. Poor convergence does not. The slot index decides the outcome. Raise the slot index enough to keep light confined across each slot. A radiating structure becomes a true reflector, and the dip deepens by more than an order of magnitude. Broad sampling of this design space now trains a network predicting the guided field for a new design. We will release the programs and all settings openly.

Introduction

Fiber Bragg gratings are periodic index modulations written into a fiber core; they reflect a narrow band around the Bragg wavelength and transmit the rest [1]. Their design rests almost universally on coupled-mode theory, which treats the grating as a weak perturbation coupling two counter-propagating guided modes [2]. That treatment assumes the field stays guided everywhere along the structure, an assumption that fails at high index contrast or across deep low-index slots, where the field diffracts sideways and the measured dip need not report reflection. Machine learning offers a practical route through the resulting design space: a surrogate trained on converged solutions replaces individual full-wave evaluations at negligible cost [3], and gradient-boosted trees suit the smooth parameter maps encountered here [4]. We therefore solve Maxwell's equations for the full cylindrical geometry without the weak-index assumption, cross-validate two independent solvers, and identify the parameter that separates guided from radiating behaviour.

Key results

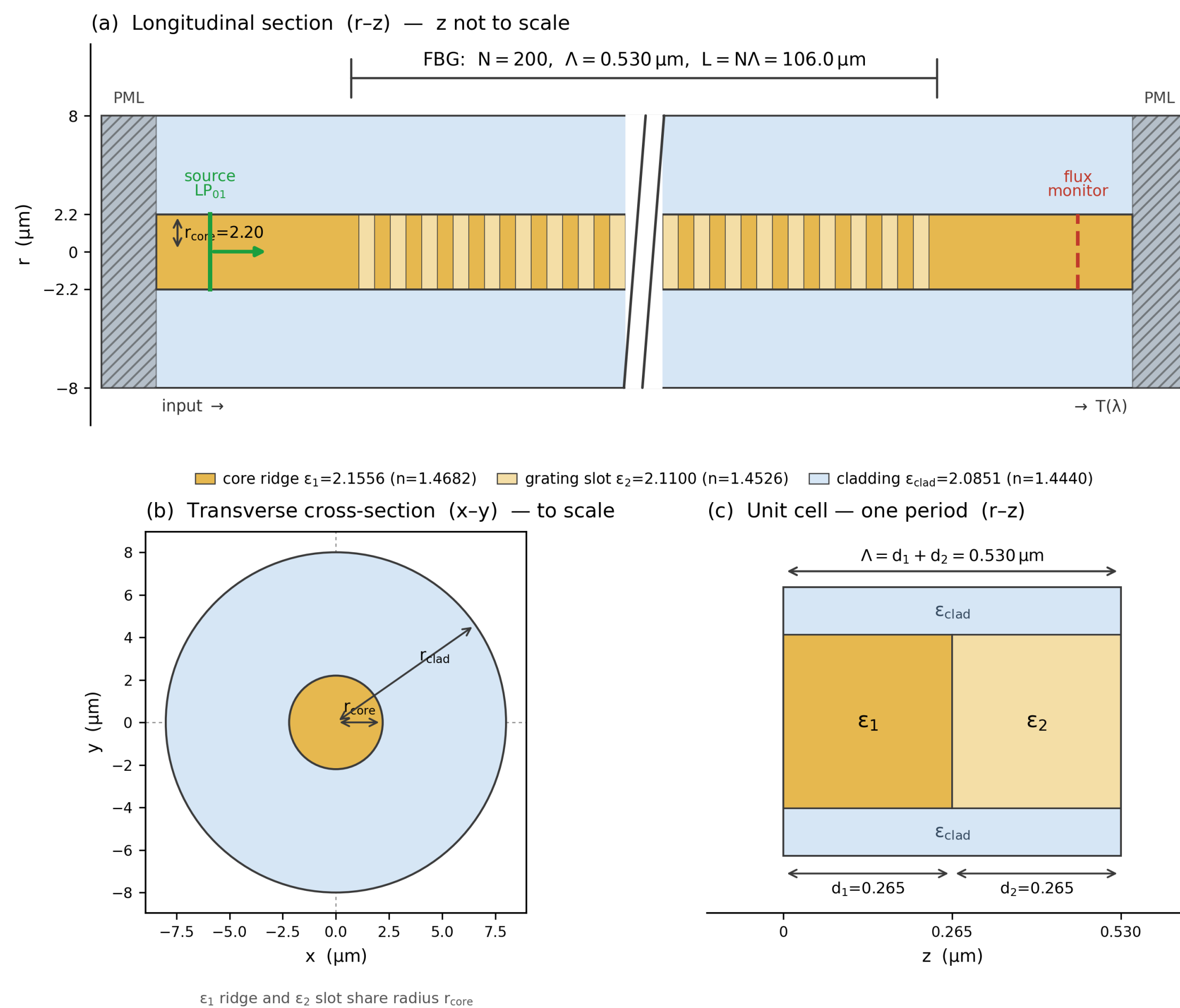
< 1%

agreement between the two solvers on the Bragg condition

$R^2 = 0.9873$

surrogate accuracy for $\Delta f/f$ over 3 652 converged solves

Cylindrical fiber Bragg grating — structure and parameters



(d) Parameters

Geometry & materials		
Core radius	r_{core}	2.20 μm
Cladding radius (model)	r_{clad}	8.00 μm
Grating period	Λ	0.530 μm
Ridge width	d_1	0.265 μm
Slot width	d_2	0.265 μm
Duty cycle	d_2/Λ	0.50
Number of periods	N	200
Grating length	$L = N\Lambda$	106.0 μm
Core permittivity	ϵ_1	2.1556
Slot permittivity	ϵ_2	2.1100*
Cladding permittivity	ϵ_{clad}	2.0851
Azimuthal order	m	0 (LP_{01})
FDTD resolution		64 px/ μm
Derived (coupled-mode theory)		
Numerical aperture	NA	0.266
V-number @ 1.55 μm	V	2.37 (SM)
Index modulation	Δn	0.0156
Effective index	n_{eff}	1.4638
Bragg wavelength	λ_B	1551.7 nm [†]
Coupling coeff.	κ	0.0259 μm^{-1}
Coupling strength	κL	2.75
Reflectivity	$R = \tanh^2 \kappa L$	0.984
3-dB bandwidth	$\Delta \lambda$	13.6 nm

* guided slot. Setting $\epsilon_2 = \epsilon_{\text{clad}} = 2.0851$ makes the slot radiating; coupled-mode theory then gives $\kappa L = 4.26$, $R = 0.999$.
† coupled-mode estimate; the full-wave dip lies at 1547.7 nm.

2. Cross-validation

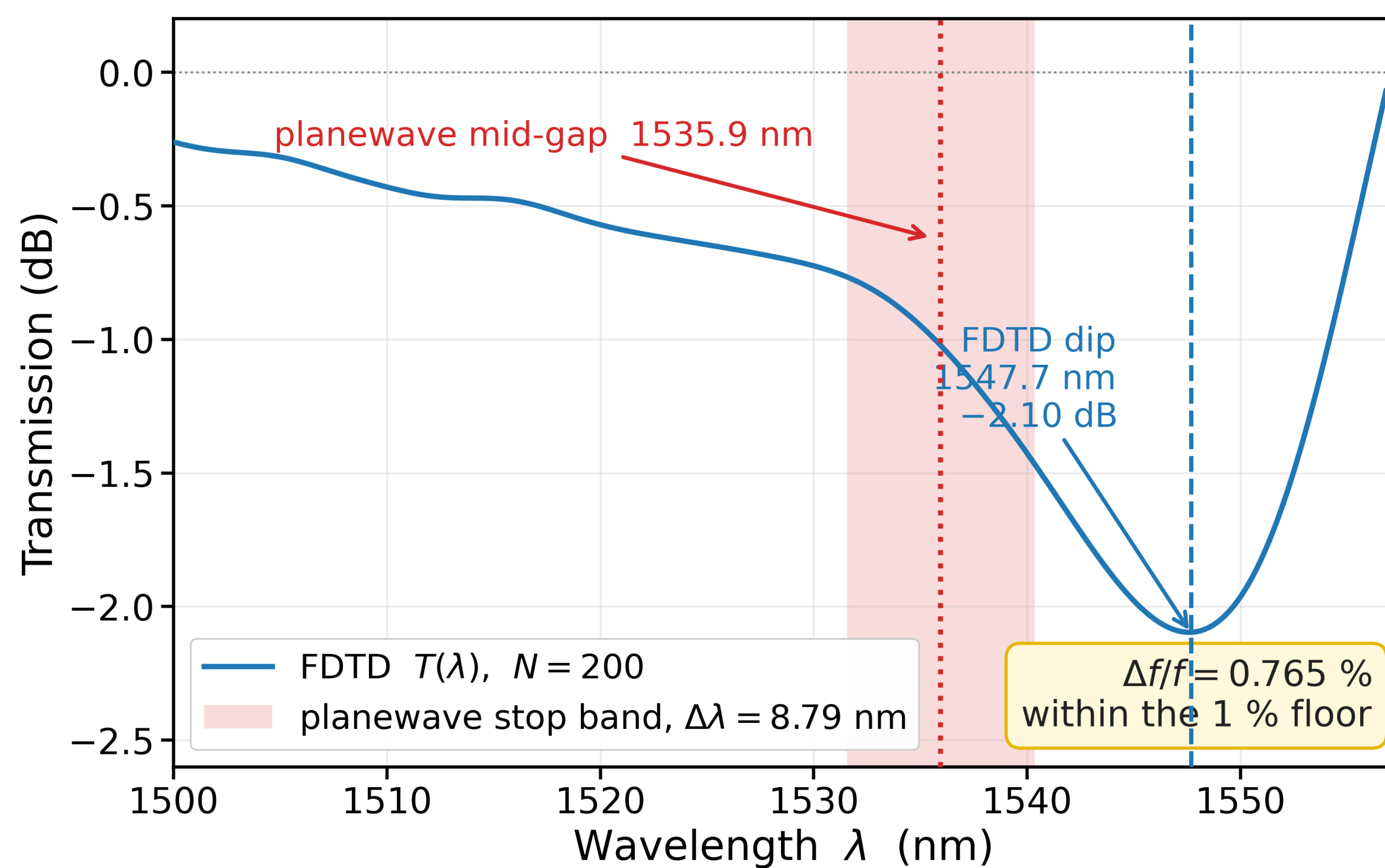


Fig. 2: MPB places the stop-band centre at 1535.9 nm (bands 2 ↔ 3, $\Delta\lambda = 8.79$ nm); MEEP places the transmission dip at 1547.7 nm. The two agree to 0.765 % in frequency — inside the 1 % finite-grating floor for $N = 200$.

3. The dip reports leakage

Predicted vs. computed reflectivity, $\epsilon_2 = \epsilon_{\text{clad}}$

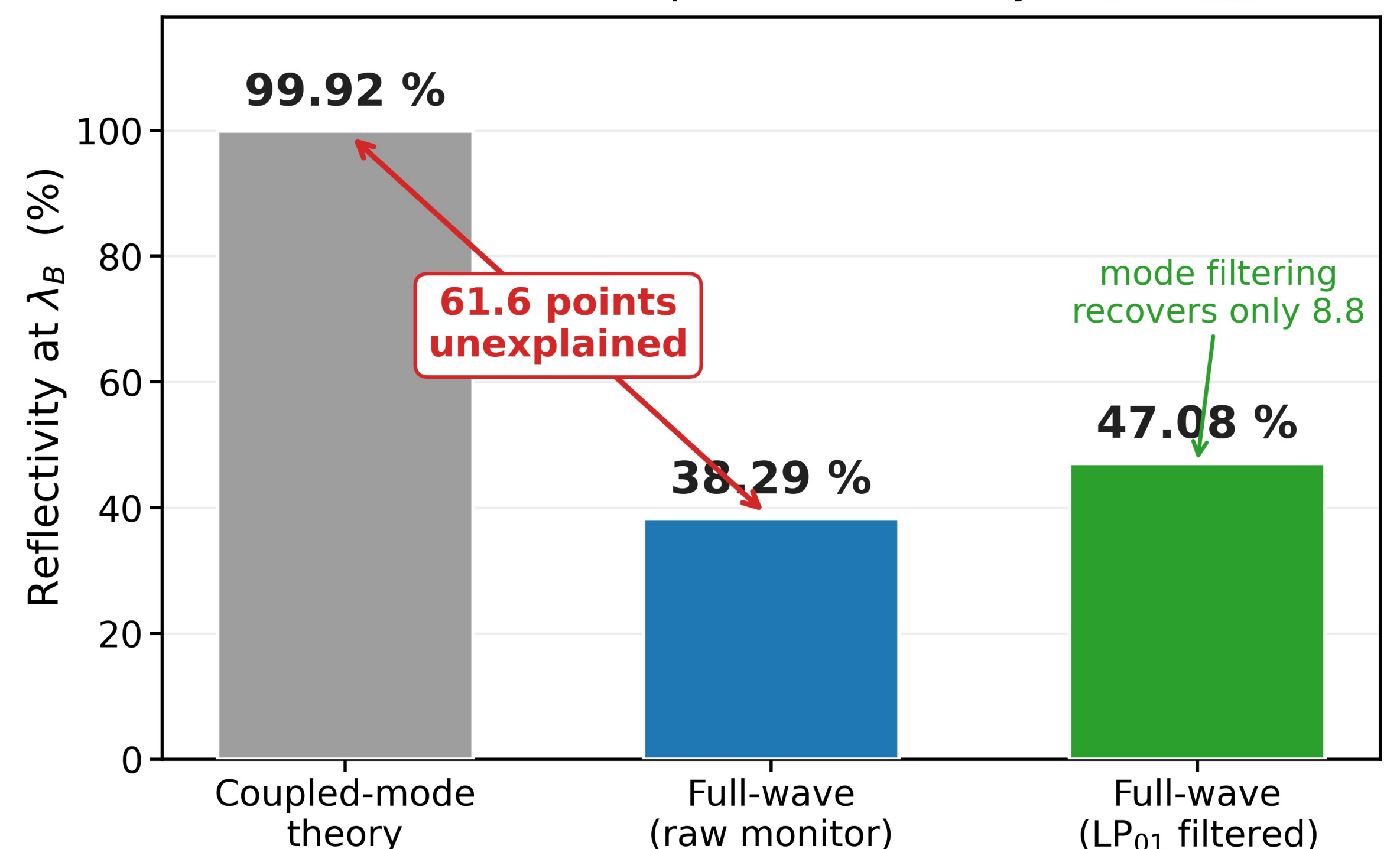


Fig. 3: Coupled-mode theory predicts $R = 99.92\%$ at $\kappa L = 4.263$. The full-wave solution returns 38.29 %. Mode-filtered monitors were predicted to recover 99.9 % — they returned 47.08 %. The surviving 52.8-point shortfall is radiation loss.

4. The slot index decides the outcome

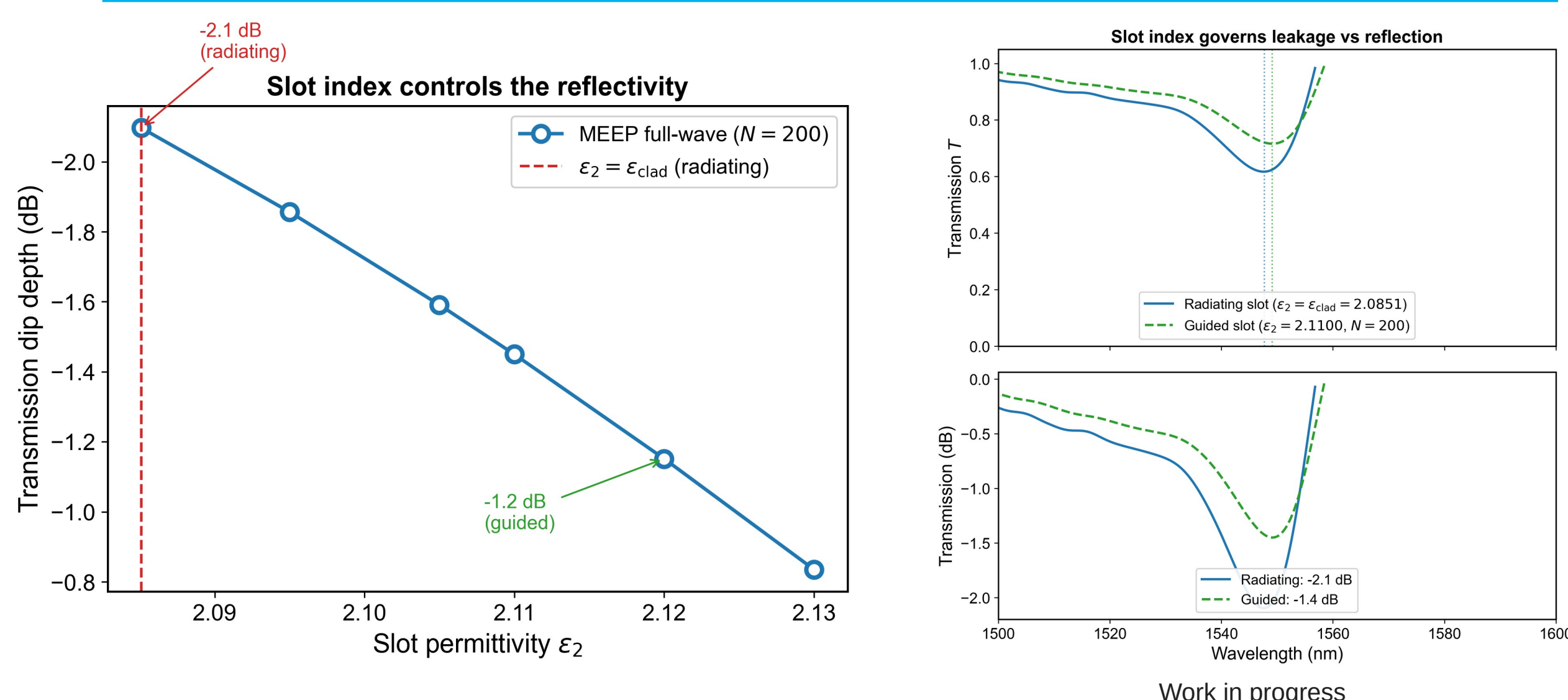


Fig. 4: With a guided slot ($\epsilon_2 = 2.1100$) the reachable dip depends on grating length. At $N = 200$ coupled-mode theory allows -6.3 to -18.0 dB; ten times deeper in dB needs $N \approx 460$.

5. Machine-learning surrogate

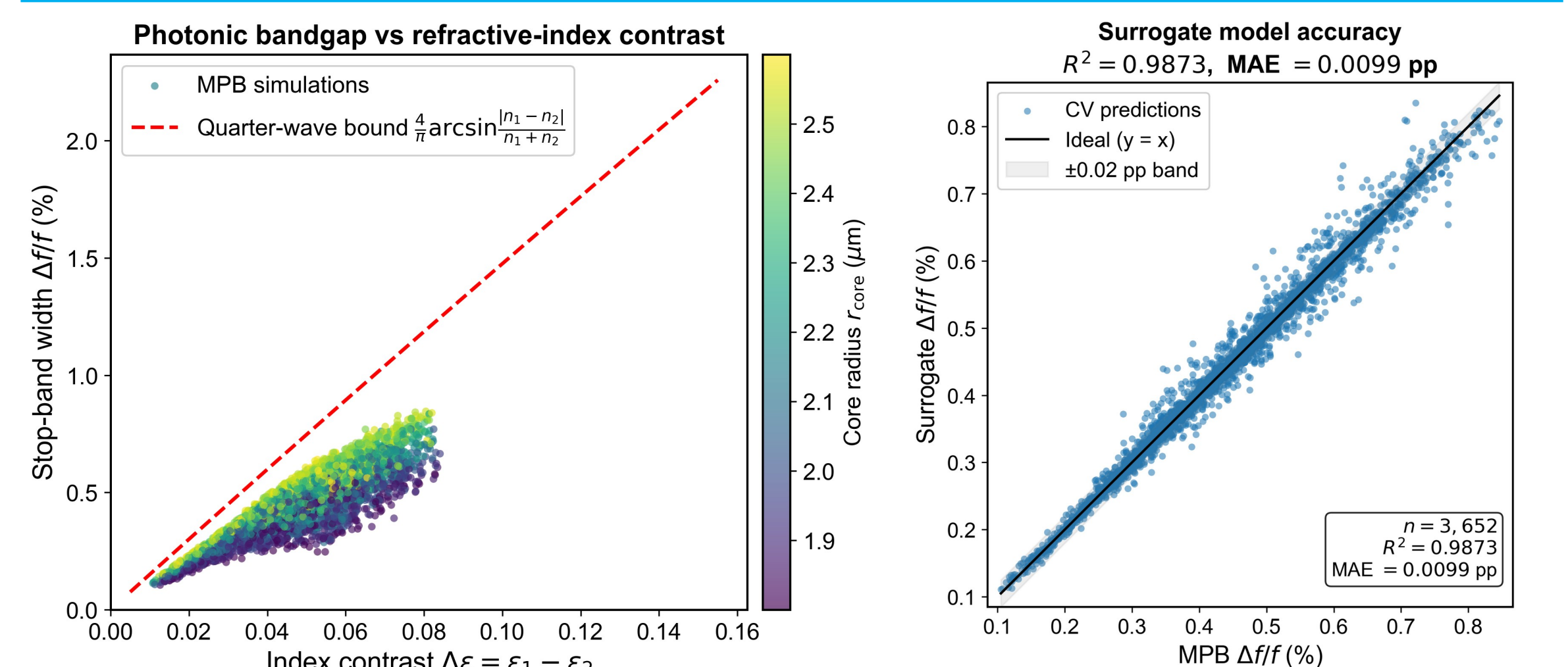


Fig. 5: 3 652 converged MPB solves over $(\epsilon_1, \epsilon_2, r_{\text{core}})$ at fixed $\Lambda = 530$ nm. Every solve sits below the bulk quarter-wave bound at a mean ratio of ~ 0.64 — the modal overlap factor. A gradient-boosting surrogate reproduces $\Delta f/f$ to $R^2 = 0.9873$.

Conclusions

Full-wave analysis is mandatory for high-contrast fiber Bragg gratings, where coupled-mode theory cannot distinguish reflection from radiation loss and consequently overestimates the achievable reflectivity by a wide margin. The slot index emerges as the parameter governing this distinction, setting whether the structure behaves as a guided reflector or as a radiating element, and it therefore deserves explicit attention in device design rather than being fixed by convention. The surrogate developed here reproduces the full-wave response closely enough to replace individual solves during exploration, making rapid iteration over novel fiber devices practical without the computational bottleneck that full-wave modelling would otherwise impose.

References

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