Diatom-Inspired Photonic Microstructures for Scattering Recovery and Ultra-High-Q Toroidal Resonators (DIPM-Integrated TSMTR Architecture)

Technical Concept Document — 2025
Author: Harrison Saavedra

ABSTRACT

This work presents the TSMTR-V4, an advanced hybrid toroidal micro-resonator architecture engineered to maximize photon lifetime (τ_{eff}) and effective quality factor (Q_{eff}) through structured loss-management, rather than simple loss minimization. The core innovation is the separation of the functional output-momentum channel from the internal parasitic-loss recycling network.

The system integrates three key mechanisms:

1. A phase-locked Controlled Coupling Interface (CCI) defining the intentionally engineered output loss κ_{out} necessary for stable thrust generation.
2. A Micro-Recirculating Nano-Network (MRNN) that guides otherwise lost scattering back toward resonance.
3. Diatom-Inspired Photonic Microstructures (DIPMs) — biologically derived nano-faceted silica structures integrated into the inner cavity surfaces to increase internal path-length, redirect sub-wavelength scattering, and suppress parasitic loss.

The total loss rate is expressed as:

$$\kappa_{\text{tot}} = \kappa_{\text{int}} + \kappa_{\text{abs}} + \kappa_{\text{scat}} + \kappa'_{\text{ext}} + \kappa_{\text{out}}$$

where the residual parasitic loss after scattering-recovery is:

$$\kappa'_{\text{ext}} = (1 - \eta_p)\kappa_{\text{ext,p}}$$

and:

$$\eta_p = \eta_{\text{MRNN}}\, \eta_{\text{DIPM}}\, \eta_{\text{reinj}}$$

This hybrid separation between κ_{out} and κ'_{ext} enables photon lifetime extension without compromising momentum transfer. With efficient scattering-recovery, the system supports $Q_{eff} \geq 10^7$, enabling compact photonic propulsion and long-duration optical energy storage.

I. INTRODUCTION

Photonic propulsion is fundamentally limited by thrust scaling:

$$F = \frac{P_{\text{out}}}{c}$$

Thus, maximizing the internal circulating power P_{circ}requires cavities with extremely long photon lifetimes and suppressed parasitic losses.

Traditional resonator research focuses on reducing:
κ_abs (material absorption)
κ_scat (surface scatter)
κ_ext,p (parasitic leakage)

However, even nanometer-scale defects dominate κ_tot at high Q, making purely passive loss-minimization insufficient.

Hybrid Loss-Engineering (HLE)

The TSMTR-V4 introduces Hybrid Loss-Engineering, where loss is not minimized globally; rather it is partitioned functionally:

- κ_out is deliberately engineered to extract momentum (thrust).
- κ_ext′ is processed by the MRNN–DIPM network and reinjected into the resonant mode.
- Only unrecovered loss contributes negatively to τ_eff.

This approach allows stable high-Q operation even under:

- thermal drift,
- mechanical deformations,
- Doppler shift in deep space,
- long-duration propagation without active stabilization.

II. ARCHITECTURE OVERVIEW

Components:

1. Toroidal Resonator Core
   Supports Whispering Gallery Modes (WGMs) with baseline Q ~10^6.
2. Controlled Coupling Interface (CCI)
   Defines κ_out.
   Implements phase-locked directional extraction.
3. Micro-Recirculating Nano-Network (MRNN)
   Sub-wavelength tunnels along the internal wall guiding scattered photons back.
4. Diatom-Inspired Photonic Microstructures (DIPMs)
   Nano-faceted silica “photonic lenses” inspired by diatom frustules.
5. Reinjection Alignment Layer
   Ensures mode-profile overlap for photons recovered via MRNN.

III. PHOTON LIFETIME EXTENSION MECHANISM

A. Total Loss Model

$$\kappa_{\text{tot}} = \kappa_{\text{int}} + \kappa_{\text{abs}} + \kappa_{\text{scat}} + \kappa'_{\text{ext}} + \kappa_{\text{out}}$$

B. Parasitic Loss Recovery

Original parasitic scattering:

$$\kappa_{\text{ext,p}}$$

Recovered portion:

$$\eta_p \kappa_{\text{ext,p}}$$

Residual escape:

$$\kappa'_{\text{ext}} = (1 - \eta_p)\kappa_{\text{ext,p}}$$

Where:

- η_MRNN — guided-path recovery efficiency
- η_DIPM — nano-lensing angular correction
- η_reinj — overlap efficiency with original WGM

Because each process is multiplicative and cascaded, the product model is correct.

IV. THRUST MODEL

Fraction of circulating power extracted for thrust:

$$\frac{P_{\text{out}}}{P_{\text{circ}}} \approx \frac{\kappa_{\text{out}}}{\kappa_{\text{tot}}}$$

Net thrust:

$$F = \frac{P_{\text{out}}}{c}$$

By isolating κ_out from all other losses, thrust becomes predictable and independent of microscopic cavity imperfections.

V. DOPPLER AND DETUNING STABILITY

Deep-space motion causes:

- Doppler shift
- Mode detuning
- Phase-slip in CCI extraction

TSMTR-V4 mitigates these through:

1. Low κ_tot (long τ_eff) → increases linewidth tolerance.
2. DIPM scattering-correction → maintains stable mode profile.
3. Phase-locked CCI → dynamically re-centers the coupling.

This directly addresses Philip's concern about far-field Strehl degradation and return Doppler shift.

VI. MATERIALS & FABRICATION

- Fused silica base.
- Integrated DIPM nano-facets (200–600 nm).
- MRNN etched channels (50–200 nm).
- Surface roughness $<$ 0.3 nm RMS.
- Outer ring supports thermal isolation.

VII. DISCUSSION

TSMTR-V4 provides a unique path toward structured loss-engineering, redefining how high-Q cavities can operate beyond fundamental manufacturing tolerances.

Rather than fighting scattering loss, the architecture absorbs it into the design, converting it into extended photon lifetime.

VIII. CONCLUSION

The TSMTR-V4 presents a realizable, high-rigor conceptual model for hybrid toroidal resonators capable of stable long-τ, high-Q operation while maintaining controlled thrust extraction.
The DIPM and MRNN networks represent a new class of scattering-management technologies applicable to photonic propulsion, optical memory, and energy-dense photon storage.