TSMTR-V4: Hybrid Toroidal Resonator With Integrated Micro-Faceted Photon Pipeline for Enhanced Photon Lifetime and Controlled Thrust Output

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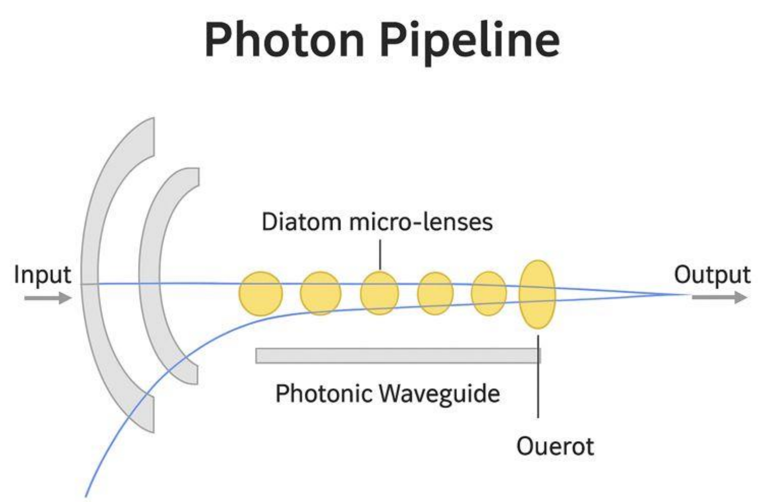
ABSTRACT

This work presents the TSMTR-V4, an upgraded hybrid toroidal resonator architecture designed to extend photon lifetime and increase the effective quality factor (Q_{eff}) through engineered loss management, micro-faceted scattering control, and a bio-inspired internal collimation system.

The system integrates:
(1) a phase-matched Controlled Coupling Interface (CCI) that defines the functional thrust extraction loss κ_{out};
(2) a Micro-Recirculating Nano-Network (MRNN) that converts parasitic scattering $\kappa_{ext,p}$ into guided trajectories; and
(3) a **Micro-Faceted Photon Pipeline (MFPP)** composed of nano-structured scattering centers and micron-scale biological-inspired lenses that increase path length and stabilize photon escape through a tuned outlet channel.

The total cavity loss is formally:
$\kappa_{tot} = \kappa_{int} + \kappa_{abs} + \kappa_{scat} + \kappa_{ext}' + \kappa_{out}$
with
$\kappa_{ext}' = (1 - \eta_p)\, \kappa_{ext,p}$
representing the unrecycled parasitic loss after MRNN+MFPP recovery.

This architecture strengthens τ_{eff}, stabilizes $Q_{eff} \geq 10^7$, and maintains a single controlled momentum-transfer channel for measurable radiation-pressure thrust.



I. INTRODUCTION

Radiation-pressure propulsion requires ultra-high circulating optical power and photon lifetimes far above those of conventional whispering-gallery (WG) resonators. Practical limitations emerge from parasitic scattering, intrinsic material losses, and uncontrolled external leakage.

The TSMTR program aims to create a closed-loop loss-managed cavity capable of redirecting, delaying, or reconverting photons that would otherwise escape.

TSMTR-V4 introduces a new subsystem:
the Micro-Faceted Photon Pipeline (MFPP), merging engineered nano-facets with micro-lenses inspired by diatom biosilica to guide scattered photons into a controlled escape path.

II. BACKGROUND AND MOTIVATION

Conventional WG resonators lose photons primarily through:
• surface scattering (κ_{scat})
• parasitic external escape ($\kappa_{ext,p}$)
• imperfect total internal reflection (TIR)

Attempts to mitigate this typically focus on surface polishing, improved materials, or mode-shaping.

TSMTR-V4 expands the loss-engineering philosophy:
instead of *avoiding* the scattering, we *harvest* it and convert it into functional recirculation using internal micro-structures.

MRNN (TSMTR-V2/V3) proved conceptually strong.
TSMTR-V4 adds the MFPP to channel these photons toward a controlled outlet interface with minimal phase disorder.

III. SYSTEM ARCHITECTURE

The system uses a Triple-Stage Cavity Management Strategy (TCMS):

1. **Injection** (input coupler)
2. **Amplification** (toroidal WG resonance)
3. **Recycling** (MRNN + MFPP)

A. Toroidal Resonator

The main cavity is a high-index toroid operating in WG mode. Its geometry allows long optical paths with minimal intrinsic loss and supports controllable external coupling via the CCI.

B. Controlled Coupling Interface (CCI)

The CCI defines the only *functional* loss κ_{out}. It controls thrust by extracting a precise power fraction:

$P_{out} / P_{circ} \approx \kappa_{out} / \kappa_{tot}$
$F = P_{out} / c$

The CCI is isolated from all recycling mechanisms (MRNN & MFPP) to ensure thrust does not mix with parasitic channels.

C. Micro-Recirculating Nano-Network (MRNN)

The MRNN uses nano-facets, pits, tunnels, and micro-interfaces etched into the near-surface region of the toroid.

Function:
• capture photons about to escape
• force multi-bounce internal paths
• redirect them to the MFPP inlet

The MRNN increases path length → increases τ_{eff} → increases Q_{eff}.

D. Micro-Faceted Photon Pipeline (MFPP)

(Nueva Innovación de TSMTR-V4)

The MFPP is a narrow engineered tunnel running from the MRNN scattering zone to the controlled outlet.

The MFPP contains two main optical elements:

1. Internal Micro-Lens (IML)

Located just inside the pipeline entrance. Inspired by diatom silica structures, functioning as a micro-collimator:

• corrects phase disorder
• compresses the scattered photon bundle
• stabilizes the mode entering the tunnel
• increases η_p (recycling efficiency)

2. Internal Micro-Lens II (Outlet Collimator)

Placed at the exit of the pipeline, still *inside* the resonator boundary.
Purpose: narrow the angular output distribution to minimize scattering back into $\kappa_{ext,p}$ and guide the photon into either:

• the external re-injection system (if closed-loop)
or
• the CCI thrust path (if configured for contribution to κ_{out})

Guided Tunnel Geometry

The MFPP tunnel is lined with micro-faceted scattering elements that act as controlled internal reflectors.
This prevents photons from drifting into random internal regions and increases the probability of reaching the outlet.

The MFPP effectively **turns parasitic loss into a guided optical circuit.**

IV. PHOTON RECIRCULATION MODEL

The total loss:

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

where:

$$\kappa_{ext}' = (1 - \eta_p)\, \kappa_{ext,p}$$
$$\eta_p = \text{efficiency of MRNN + MFPP}$$

A. Photon Lifetime and Quality Factor

$$\tau_{eff} = 1 / \kappa_{tot}$$
$$Q_{eff} = \omega\, \tau_{eff}$$

Reducing κ_{ext}' via MFPP directly raises Q_{eff}.

B. Thrust-to-Power Relationship

$$F = P_{out} / c$$
$$P_{out} / P_{circ} \approx \kappa_{out} / \kappa_{tot}$$

TSMTR-V4 improves P_{circ} by raising τ_{eff}. This increases F without increasing κ_{out}.

V. EXPERIMENTAL PATHWAY

Stage 1 — CCI Testing

Measure κ_{out} stability and thrust power extraction.

Stage 2 — MRNN + MFPP Fabrication

Fabricate MFPP tunnels using FIB/e-beam lithography.
Test micro-lens alignment and photon recovery efficiency.

Stage 3 — Integrated Toroid Array

Verify stability, thermal behavior, Q_{eff} scaling, and mode persistence.

VI. EXPECTED PERFORMANCE

• Lower κ_{ext}'
• Higher τ_{eff}
• Higher Q_{eff}
• Improved directionality at output
• Lower phase noise
• Better control over thrust vectoring
• Reduced sensitivity to scattering defects

MFPP offers a strong improvement over V2/V3.

VII. CONCLUSION

TSMTR-V4 introduces a bio-inspired, micro-faceted photon management system that converts unavoidable parasitic scattering into useful, guided optical circulation.

The Micro-Faceted Photon Pipeline (MFPP):

• increases photon lifetime
• stabilizes WG modes
• enhances recycling efficiency
• reduces total external loss
• strengthens thrust predictability via CCI

This architecture delivers a viable pathway toward compact optical propulsion systems with $Q_{eff} \geq 10^7$.