PHOTON LIFETIME ENGINEERING IN A HYBRID TOROIDAL RESONATOR USING CONTROLLED COUPLING AND MICRO-RECYCLATION (TSMTR-V3 ARCHITECTURE

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ABSTRACT

This work presents the TSMTR-V3, an advanced hybrid toroidal resonator architecture designed to extend photon lifetime (τ_{eff}), increase the effective quality factor (Q_{eff}), and enable sustained radiation-pressure propulsion through engineered loss management.

The system incorporates two synergistic mechanisms:
(1) a phase-matched Controlled Coupling Interface (CCI), which defines the sole functional output loss channel (κ_{out}) for thrust generation, and
(2) a Micro-Recirculating Nano-Network (MRNN), a sub-wavelength engineered structure that converts parasitic scattering ($\kappa_{ext,p}$) into recoverable energy before reinjection.

The total loss rate is expressed as:

$\kappa_{tot} = \kappa_{int} + \kappa_{abs} + \kappa_{scat} + \kappa_{ext}' + \kappa_{out}$
with $\kappa_{ext}' = (1 - \eta_p)\, \kappa_{ext,p}$ representing unrecovered parasitic loss.

The V3 architecture ensures that the recycling channel (MRNN) maximizes τ_{eff} by minimizing κ_{ext}', while the CCI maintains a stable κ_{out} that guarantees a predictable thrust pathway

($F = P_{out} / c$). This combined mechanism establishes a rigorous and physically grounded pathway toward $Q_{eff} \geq 10^7$ in compact dielectric resonators relevant to photonic propulsion and advanced optical systems.

I. INTRODUCTION

Propellantless photonic propulsion requires extreme optical efficiency due to the inherently small force produced by radiation pressure. Achieving meaningful thrust demands circulating optical power (P_{circ}) that exceeds the input power (P_{in}) by orders of magnitude. This condition is only achievable in resonators operating with ultra-high quality factors ($Q \geq 10^7$).

Conventional dielectric resonators face two fundamental limitations:

1. intrinsic material losses (κ_{int}, κ_{abs}), and
2. external parasitic losses ($\kappa_{ext,p}$) arising from scattering, fabrication roughness, and unavoidable discontinuities.

These external losses dominate the loss budget and prevent photon lifetimes from reaching the required regime for propulsion.

The TSMTR-V3 introduces an engineered strategy that treats loss not merely as a quantity to minimize, but as a channel to reshape. The architecture integrates controlled output coupling with engineered internal micro-recirculation to increase photon lifetime while preserving a dedicated thrust channel.

II. BACKGROUND AND MOTIVATION

Radiation-pressure propulsion requires long photon confinement times. Existing approaches—high-Q optical cavities, photonic crystals, and multi-mirror recycling schemes—are all ultimately limited by uncontrolled scattering.

The motivation of the TSMTR-V3 architecture is to convert the dominant loss mechanism (parasitic scattering) into functional recirculation. Instead of regarding $\kappa_{ext,p}$ as wasted optical energy, the MRNN transforms it into delayed, guided re-injection.

This approach addresses three major limitations in photonic propulsion research:

1. **Photon lifetime ceiling** set by uncontrolled scattering.
2. **Instability from nonlinearity** (thermal and Kerr effects).
3. **Lack of a clean output port** for thrust without degrading Q.

TSMTR-V3 directly tackles all three simultaneously.

III. SYSTEM ARCHITECTURE

The system operates using a Triple-Stage Cavity Management strategy:

1. **Injection**
2. **Amplification**
3. **Recycling**

A. Toroidal Resonator Core

The dielectric toroidal micro-resonator confines Whispering-Gallery **(WG)** modes with minimal intrinsic losses. Optional active gain media (e.g., Yb:YAG) may enhance P_{circ} for propulsion applications.

B. Controlled Coupling Interface (CCI)

The CCI is a phase-matched micro-port that:

- extracts a controlled fraction of P_{circ}
- defines the functional loss rate κ_{out}
- provides the sole directional thrust output
- remains isolated from all recycling channels

This ensures that the thrust force $F = P_{out} / c$ is stable and predictable.

C. Micro-Recirculating Nano-Network (MRNN)

The MRNN is the central innovation of the V3 architecture.

It consists of engineered nano-facets or micro-tunnels embedded near the resonator's boundary. Their function is to:

- intercept photons that fail the total-internal-reflection condition
- force them through controlled multi-bounce internal trajectories
- extend their dwell time before exiting
- guide them into the Recycled-Flow Channel (RFC)

This transforms $\kappa_{ext,p}$ (random scattering) into a reduced loss term:

$\kappa_{ext}' = (1 - \eta_p)\, \kappa_{ext,p}$
with η_p representing **MRNN** recycling efficiency.

D. Hybrid Loss-Engineering Framework

The TSMTR-V3 strictly separates:

- **κ_{out} → thrust channel**
- **$\kappa_{ext,p}$ → recycled channel**
- **κ_{ext}' → unrecoverable loss**

This separation produces a stable, analyzable, and optimizable Q_{eff}.

IV. PHOTON RECIRCULATION AND THRUST MODEL

A. Total Loss Rate

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

B. Photon Lifetime and Q-Factor

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

C. Thrust Efficiency

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

This relationship ensures the thrust is proportional to the controlled output loss, not to uncontrolled cavity imperfections.

V. EXPERIMENTAL PATHWAY

Stage 1 — CCI Validation

Measure κ_{out} and P_{out} in a controlled benchtop resonator.

Stage 2 — MRNN Validation

Fabricate MRNN patches using electron-beam lithography.
Measure increases in τ_{eff} and reductions in κ_{ext}'.

Stage 3 — Integrated System Modeling

Simulate the full resonator, including thermal, nonlinear, and stability effects, and model architecture variants including multi-resonator arrays.

VI. EXPECTED PERFORMANCE

Simulations predict sustained operation at $Q_{eff} \geq 10^7$ under conservative assumptions.
Photon lifetime extension depends primarily on η_p and suppression of κ_{ext}'.
Array configurations (3–4 resonators) allow thrust vectoring and improved thermal stability.

VII. CONCLUSION

The TSMTR-V3 is a rigorously engineered resonator architecture that converts parasitic losses into functional recirculation while preserving a dedicated output channel for thrust. This hybrid strategy increases photon lifetime, stabilizes cavity behavior, and provides a physically grounded pathway toward photonic propulsion systems requiring ultra-high Q.

Further resources are requested for detailed numerical modeling, experimental fabrication of MRNN structures, and full benchtop demonstration.

REFERENCES

[To be completed by PI]