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Selective modal excitation of a nanophotonic cavity with a programmable phase mask

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Abstract: Selective spatial mode excitation of a grating-coupled multimode micro-cavity is achieved using an incident beam shaped with a programmable phase mask. Real-time control of the phase mask coupled to differential evolution algorithm allows access to individual modes with high selectivity up to the tenth order. © 2024 The Author(s)

1. Introduction

Addressing specific spatial modes in photonic devices has become crucial for advancing optical communication and computing technologies. Selective mode excitation and control facilitate enhanced optical transmission capacities through spatial division multiplexing [1], enable efficient mode combinations for photonic-based computing cores [2], and support the creation of dynamically reconfigurable systems for a broad range of applications, from neuromorphic computing to quantum information technologies [3].

In this context, we present an approach to selectively excite spatial modes in a grating-coupled micro-cavity, termed a Cavity Resonator Integrated Grating Filter (CRIGF), using a programmable phase mask. By shaping the incident beam's profile with a phase-only Spatial Light Modulator (SLM) and employing a differential evolution algorithm, we achieve high-selectivity access to individual modes up to the tenth order. Although the actual proof-of-principle is performed hereafter on a passive (linear) device, this work could readily be extended to the nonlinear or laser regimes should the device waveguide core embed a suitable non-linear [4] or active [5, 6] material layer.

2. The Cavity-Resonator-Integrated Grating Filter (CRIGF)

Cavity-Resonator-Integrated Grating Filters (CRIGFs) [7] are a particular variant of Guided Mode Resonance Filters (GMRFs), acting as spectrally selective filters for tightly focused beams under normal incidence. As depicted in figure 1-a), a 2D CRIGF is formed by a vertical (y) and an horizontal (x) CRIGF sharing a common central area (blue). Along both x and y directions, a pair of Distributed Bragg Reflectors (DBRs, red) forms a planar Fabry-Pérot cavity (FP) for the guided mode. A few-period-long Grating Coupler (GC), centred in the FP couples the cavity mode to focused incident beam(s). Along each direction, a Phase Section (PS, green) ensures spatial and spectral overlap of the GC with the cavity mode.

Our analysis begins by mapping the structure's radiative patterns through spatial scanning, revealing distinct spectral modes characterized by unique intensity distributions along the y axis [8]. These modes, identifiable from $N = 0$ to 8 on figure 1-b), demonstrate the CRIGF's capacity for mode-specific resonance, laying the groundwork for our selective modal excitation studies.

3. Methodology and results

Selective modal excitation in our study is realized through the use of a phase-only Spatial Light Modulator (SLM) incorporated into a Fourier-transform optical setup. This arrangement allows for precise control over both the amplitude and phase of the transmitted laser beam, achieved by amplitude spatial modulation of a blazed grating on the SLM [9]. Specifically, we use this setup to generate beam profiles that mirror the spatial distribution of the radiative fields emitted by the CRIGF.

Our initial experiments target 1D profiles to excite the CRIGF's vertical cavity. Each pattern M_l , l denoting the number of nodes along the y axis, has a spatial amplitude profile $A_l(x, y)$ described by :

$$A_l(x, y) = \text{rect}\left(\frac{x}{L}, \frac{y}{L}\right) \times \{\cos(\pi y(l+1)/L) \text{ if } l \text{ is even ; } \sin(\pi y(l+1)/L) \text{ otherwise}\} \quad (1)$$

Using a wavelength-tunable laser polarized along x and shaped along y according to these profiles, we record the difference in spectral reflectivity between the center of the cavity and the thin-film response on the DBR section. This difference corresponds to the resonant reflection and the excitation of specific modes within the CRIGF.

Reflectivity measurements validated our approach, with Figure 1-c illustrating the selective excitation of modes by showing a clear diagonal pattern of high-intensity spots. This pattern signifies targeted mode excitation. However, a checkerboard pattern also emerged, as seen in the same figure, attributable to the spatial profile overlap

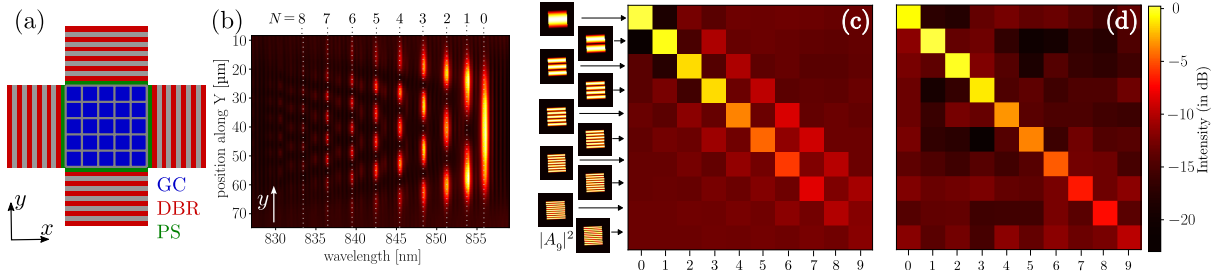


Fig. 1. a) CRIGFs under study: grating coupler (GC, blue), Distributed Bragg Reflector (DBR, red) and Phase Shifts (PS, green). b) Spectro-spatial cartography of the cavity modes. c) Modal selectivity: reflection by each mode for various field patterns $A_I(x,y)$. d) Optimized modal selectivity: reflection by each mode for various optimized field patterns.

between even and odd-numbered modes, leading to unintended cross-excitation. To enhance our modal selectivity, we applied to the experiment an evolutionary algorithm to optimize the beam profiles, involving linear combinations of the initial ten patterns.

The effectiveness of this optimization is showcased in Figure 1-d, where a sharpened diagonal pattern emerges, significantly improving modal selectivity. This refined pattern highlights the successful isolation of the target modes and the reduction of cross-excitation, affirming the efficacy of our approach.

4. Conclusion

Our study showcases the selective excitation of high-order modes within a Cavity-Resonator-Integrated Grating Filter (CRIGF) through the use of shaped excitation beams and a programmable dynamic mask. Through the strategic application of an evolutionary algorithm to refine spatial profiles, we have significantly enhanced the experimental modal selectivity to the point where it becomes detection noise limited. Notably, the achievement of two-dimensional selective excitation of higher-order modes in the CRIGF's 2D structure [10], though not presented here, marks a key advancement and we intend to further detail it in our oral contribution.

Future work could involve the use of these mode-discriminating spectral reflectors as end mirrors in a multi-mode fibre laser, as an alternative mode combiner of few-mode fibre Bragg grating [11] or to induce reconfigurable mode-selective coupling into photonics integrated circuits. Furthermore, dual-mode excitation at different wavelengths could be performed on nonlinear CRIGFs [4] with a view to explore frequency-mixing processes with various phase-matching geometries and wavelength separation for laser wavelength spectral shifting or the generation of entangled photon pairs by spontaneous parametric down conversion [12].

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