Inverse-Design In Large Photonic Gratings Enabling Efficient Photonic-to-Free-Space Mode Coupling

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Abstract

Realization of an efficient coupling between photonic sub-micrometer size modes and hundred micrometer wide free-space beams remains a main engineering hurdle to a wider acceptance of miniaturized chip-scale atomic and bio systems. The major obstacle comes from a gigantic mode mismatch between photonic and free-space waves resulting in a poor coupling efficiency. The other complication in designing photonic converters is maintaining the precise control of light polarization, intensity, and phase. Usually, forward solvers based on an analytic theory and researcher's intuition followed by numerous coarse sweep simulations are implemented to find a photonic structure with an acceptable performance. However, this approach interrogates only a scarce parameter space, often unavoidably omitting optimal solutions. Recently an inverse-design approach - a general method of optimizing complex structures that leads to a pre-defined device performance - has been successfully introduced and developed to search the full parameter space and reveal the optimal solution.

Here we demonstrate that by applying deformations to initially uniform large gratings along with the built-in gradient-based optimization algorithm, we find the optimal design of the photonic structure that is capable to reciprocally project a 100 µm-waist collimated Gaussian beam in free space from a single-mode waveguide with ≈ 1.7 dB coupling efficiency. Particularly, we use Electromagnetic Waves, Frequency Domain in COMSOL Multiphysics® as the main physics interface. Then we describe the induced spatial deformations (Deformed Geometry) in photonic grating period and duty cycle (DC) using 3rd and 4th order power polynomial functions, respectively. Throughout inverse-design optimization (Optimization), we enable both the bottom SiO2 cladding thickness and groove depth to freely deform to enhance photonic-to-free-space coupling. For that, we define an objective function to maximize the coupling efficiency from a photonic mode to a wide collimated free-space Gaussian beam. The gradient-based algorithm yields two qualitatively different solutions of the photonic grating designs depending whether we let the outcoupling free-space beam angle vary or fix it to a normal projection. In the first case, the grating travelling mode outcouples to free-space radiation resulting in a broadband photonic operation. Tuning the laser wavelength within several tens of nanometers allows for a beam-steering of the collimated free-space Gaussian beam without visible degradation in radiated power. Conversely, constraining the outcoupling angle to vertical direction results in more narrow-band surface-normal radiation enabled by slow-light standing wave resonances supported inside the photonic grating. Interestingly, the back reflected power from the optimized grating is negligible, which is in stark contrast to the uniform grating design used to project a vertical free-space beam when both a grating wave and grating mode vectors are compensated. After realizing and testing the optimized devices enabled by the computational inverse-design method, we observe a strong agreement between the experimental performance of fabricated devices and simulated results.

To conclude, we demonstrate the efficacy of the inverse design method to optimize the large photonic grating by implementing moderate deformation to the photonic structure. The resultant

design solutions show an unprecedented performance in device functionality including the coupling efficiency that are not attainable using generic computational methods.

Figures used in the abstract

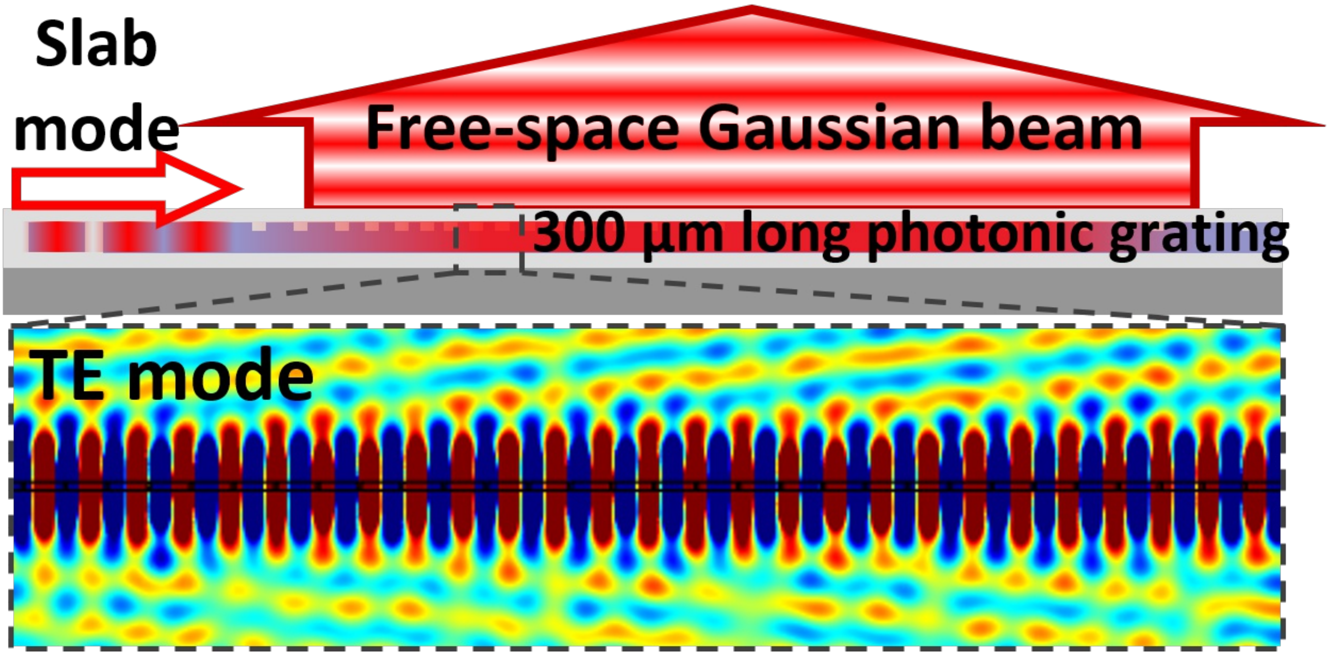

Figure 1 : Optimized performance of the deformed 300 µm long photonic grating projecting a wide collimated free-space Gaussian beam from a single-mode waveguide