Nanoholes Based Optical Phase Array for Beam Steering

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Abstract

- We present a nanoslit optical phased array on a thin gold film for compact beam steering.
- The array uses four nanoholes (50 nm width) spaced at one-quarter wavelength, each acting as a waveguide.
- By electrically tuning the refractive index inside each hole, we control the output phase per element and create a phase gradient to steer the main lobe.
- Finite-Difference Time-Domain (FDTD) simulations confirm precise, bias-controlled deflection without bulky phase shifters.
- The approach is simple and scalable, enabling tunable beam steering for integrated photonics.

Hypothesis

By adjusting the refractive index in each nanohole, we predict that the direction of the emitted beam can be dynamically tuned due to phase shifts in the transmitted light, allowing for precise beam deflection.

Introduction

- Problem: Conventional beam-steering approaches that use spatial light modulators, MEMS mirrors, or discrete phase-shifter networks are bulky and costly, limiting miniaturization.
- Concept: A thin gold film patterned with a nanoslit array forms waveguides that control the phase of transmitted light.
- Control mechanism: The refractive index inside each nanohole is tunable, allowing per-element phase control and a smooth phase gradient across the array.
- Operation: The phase gradient redirects the main beam without mechanical motion, enabling agile, on-chip steering.
- Method: FDTD simulations validate the concept and guide design choices for the metal film, dielectric infill, and array spacing.
- Impact: The approach is compact, scalable, and cost-effective, offering a practical path to integrated, tunable optical beam steering.

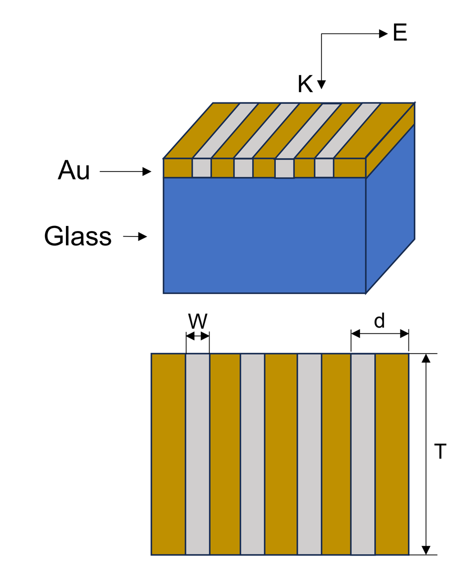
Methods

Finite-Difference Time-Domain (FDTD) Simulations:
One-Hole:

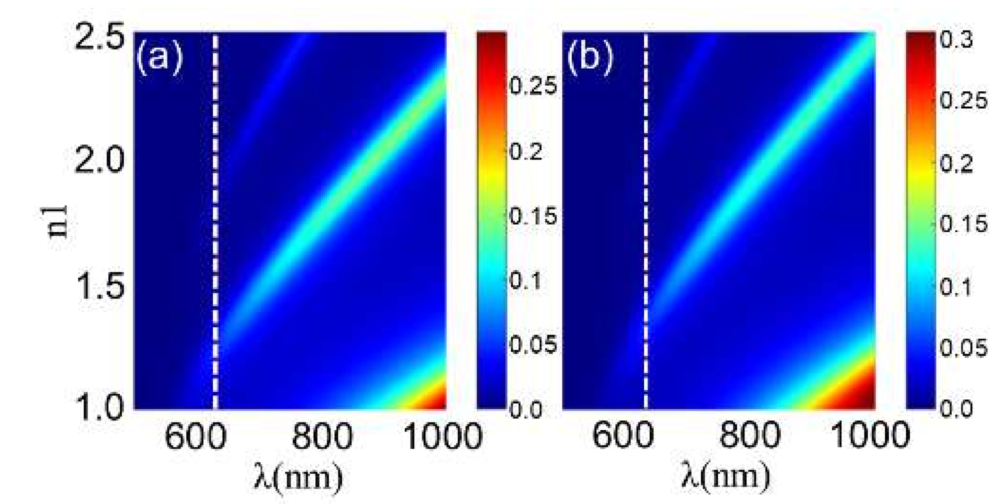
- Plane-wave source of 400nm- 1000nm normal incident.
- PML boundary conditions in X and Y directions, mesh size of 1nm.
- Hole dimensions varied with widths from 50 nm to 150 nm (10 nm increments), thicknesses from 40 nm to 300 nm, and refractive index from 1 to 5 (0.01 increments).

Four-Hole Array:

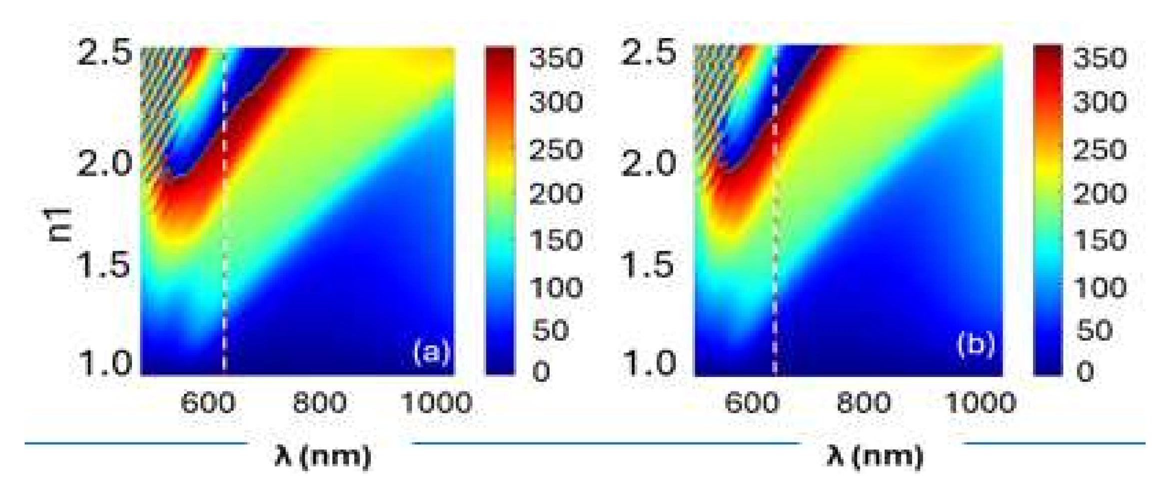
- Plane wave at 633 nm, normal incidence to the film.
- Geometry: Nanoholes with width W=50 nm; film thickness T swept over 260, 280, and 300 nm; center-to-center spacing d=208.25nm.
- Materials: Gold (Au) nanofilm using Johnson & Christy, deposited on a glass substrate.
- Additional simulation: Film thickness T = 300 nm, hole spacing d = 147 nm, and hole width w = 50 nm.



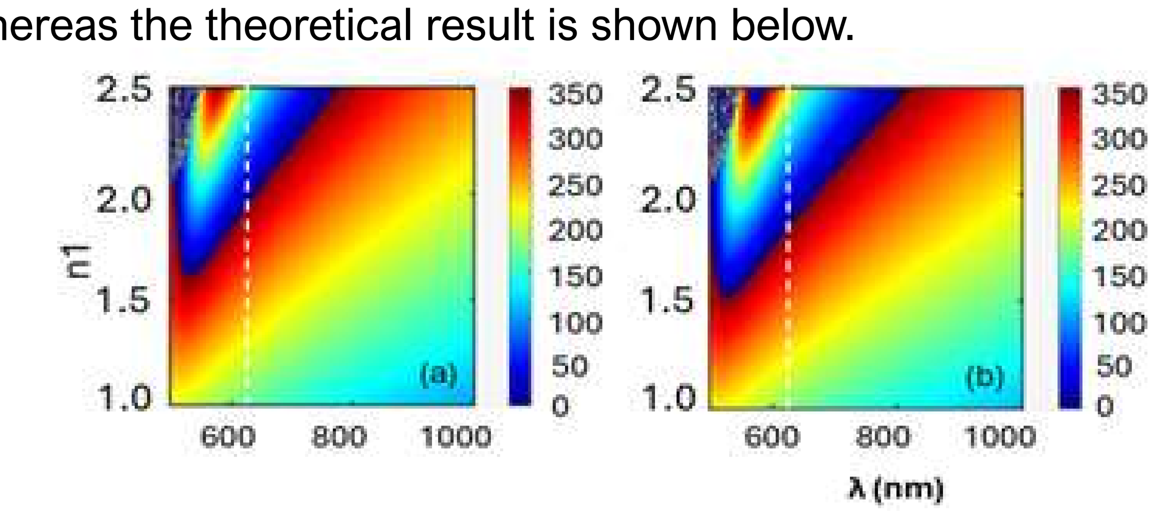
FDTD Simulation Results



- Transmitted power through a single slit with w = 50 nm and (a) T = 260 nm (b) T = 280 nm
- The single-hole simulations demonstrated a clear relationship between the refractive index (n), nanohole thickness (T), and phase shift (Δϕ)
- Doted white line at 633nm.
- Array implication: These maps were used to pick index values that produce 0°, 10°, and 20° steering in a four-hole array.



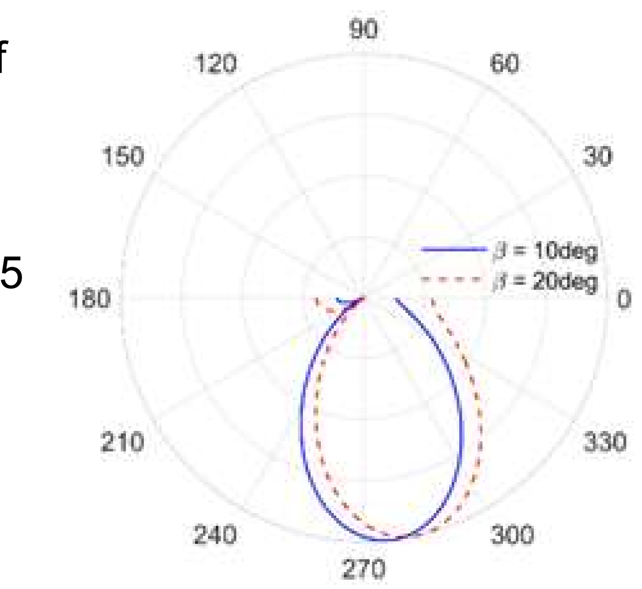
- Above figure shows the FDTD simulation results for the phase shift of a single nanoslit, whereas the theoretical result is shown below.



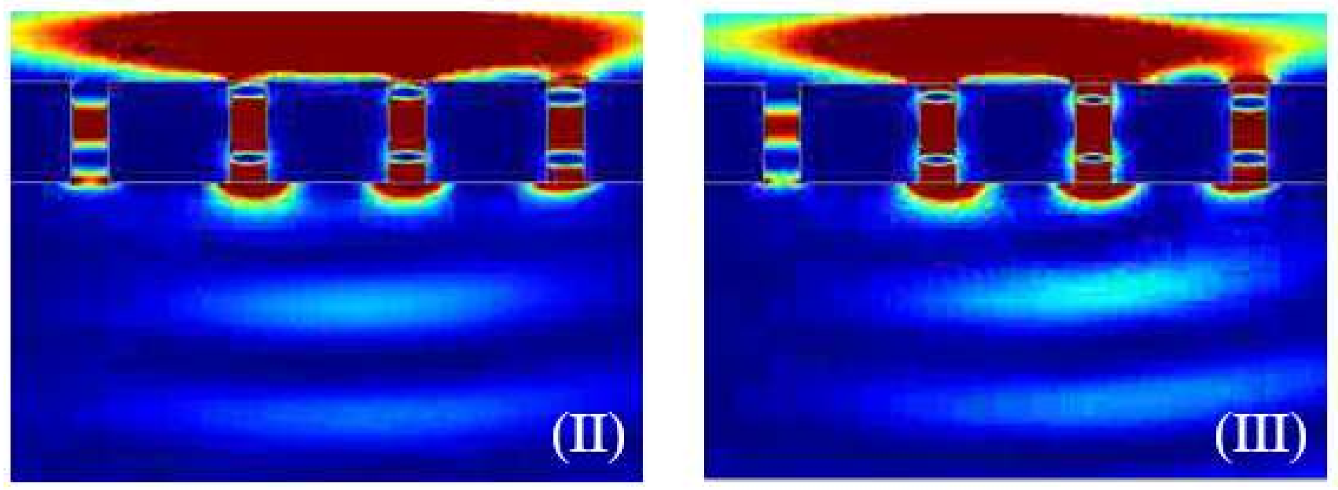
- We also performed analytical calculations for the propagation phase acquired by an SPP wave in the waveguide.
- The propagation constant of a two interface MIM waveguide can be found by solving the transcendental equation.
- We observe and excellent agreement between the analytical and simulation results.

- **FOUR-SLIT SIMULATION RESULTS**

For the operation wavelength of 633nm and element spacing of d = 208.25 nm, our analytical results using antenna array theory predict beam shift of 6.25 degrees and 12.85 degrees for phase shift β = 10 and 20 degrees, respectively.



I. Δϕ=0° (λ = 633nm,T=300nm, n[1,1,1,1]): The simulation confirmed no beam deflection.
II. Δϕ=10 (n= [1,1.04,1.08,1.12]): The simulation results showed a beam deflection angle of 6°, which is consistent with theoretical predictions of 6.25 degrees.
III. Δϕ=20 (n= [1,1.08,1.16,1.22]): The simulation results showed a beam deflection angle of 10°, which is comparable with theoretical predictions of 12.85 degrees.



Conclusion

This study demonstrates the effectiveness of using nanohole-based optical phase arrays for beam steering. By leveraging refractive index modulation within nanoscale apertures, the proposed method achieves precise beam deflection with simplicity, cost-effectiveness, and compactness. We demonstrate observable beam steering angles of 0°, 6°, and 10°, which closely align with theoretical predictions. These findings validate the approach and provide a robust foundation for further experimental exploration and the development of scalable designs.

Acknowledgments

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