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THz Atelier

Development of Hybrid phase profile silicon multi-phase zone plate lenses for THz frequencies

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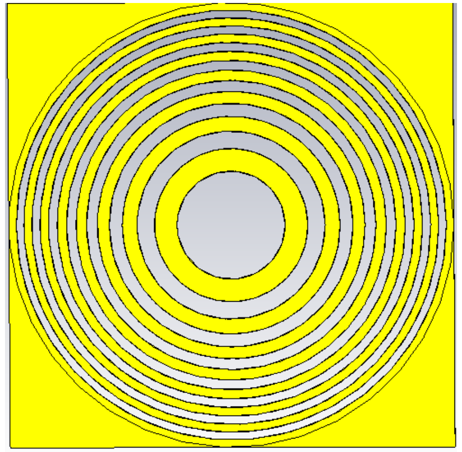
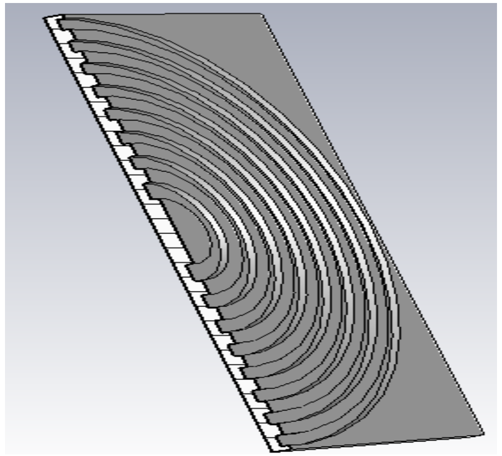
Multi-phase Zone plate Lens (MPZP): a Diffractive Optical Element (DOE) that introduce particular phase shifts of the incoming wave to create a desired phase profile of the outgoing beam with aim to focus beam at fixed focal length.

- In this case, the thickness of such structures is strictly related to the refractive index of the used material and the design wavelength.
- The Zone plates are first proposed and developed by a chemist and spectroscopist Jacques Louis Soret consisting of alternative transparent and opaque concentric rings in 18th century.
- Later, it was Robert Williams Wood who proposed a zone plate called phase-reversal zone plate by replacing opaque ring with transparent rings with a phase retardation of π radians in such a way all the zones are productive.
- From then an extensive research have been done on zone plates by several researchers and research groups in order to achieve 100% efficiency just increasing steps of phase profile.





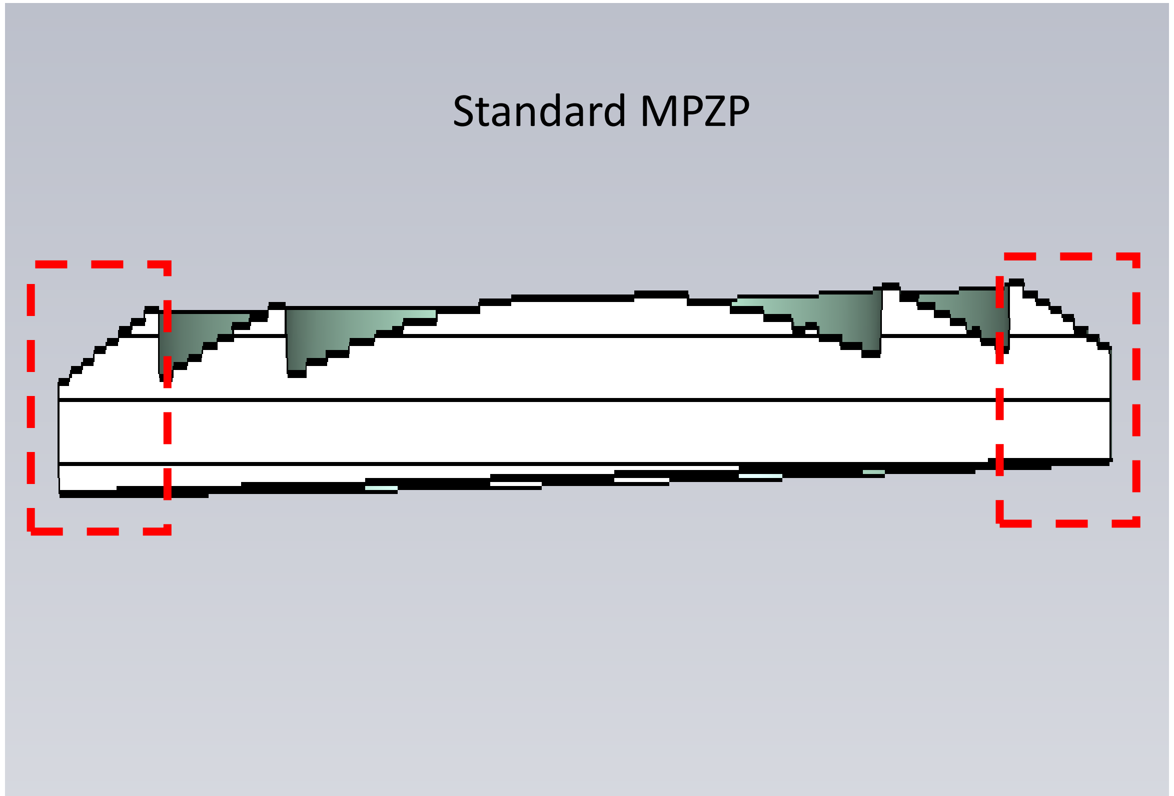
L. Minkevičius et al., "Terahertz multilevel phase Fresnel lenses fabricated by laser patterning of silicon," Opt. Lett., vol. 42, no. 10, 2017, doi: 10.1364/OL.42.001875.

Phase Coding Method	η_1
Kinoform (1st order)	100%
Kinoform (p^{th} order)	100%
Phase N-level	up to 100%
Phase 16-level	99%
Phase 8-level	95%
Phase 4-level	81%
Phase binary (2-level—with fill factor *a*)	up to 40.4%
Phase sinusoidal *	up to 33.8%
Amplitude binary (with fill factor *a*)	up to 10.1%
Amplitude sinusoidal **	up to 6.3%

A. Siemion, "The magic of optics—an overview of recent advanced terahertz diffractive optical elements," *Sensors (Switzerland)*, vol. 21, no. 1. MDPI AG, pp. 1–22, Jan. 2021, doi: 10.3390/s21010100.

Motivation

- Fabrication of such complex MPZP lenses (with such high amount of Phase steps becomes increasingly complex as the outer rings becomes narrower with the growing distance from the center.
- We need some kind of Hybrid-MPZP lenses with a hybrid phase step profile that reduces the manufacturing complexity of lens by leaving the focusing performance undisturbed of standard MPZP lens and can be suitable for much simpler on-chip photonic integration process.



$$\mathbf{r_n} = \sqrt{\frac{2\lambda\mathbf{n}\left(\mathbf{F} + \frac{\boldsymbol{d}}{2}\right)}{\mathbf{Q}} + \frac{\mathbf{n}^2\,\lambda^2}{\mathbf{Q}^2}}$$

$$\boldsymbol{d} = \frac{\lambda}{\boldsymbol{Q}(\boldsymbol{\varepsilon} - 1)}$$

H. D. Hristov, Fresnel zones in wireless links, zone plate lenses, and antennas. Artech House, 2000.

Development of the Hybrid Design

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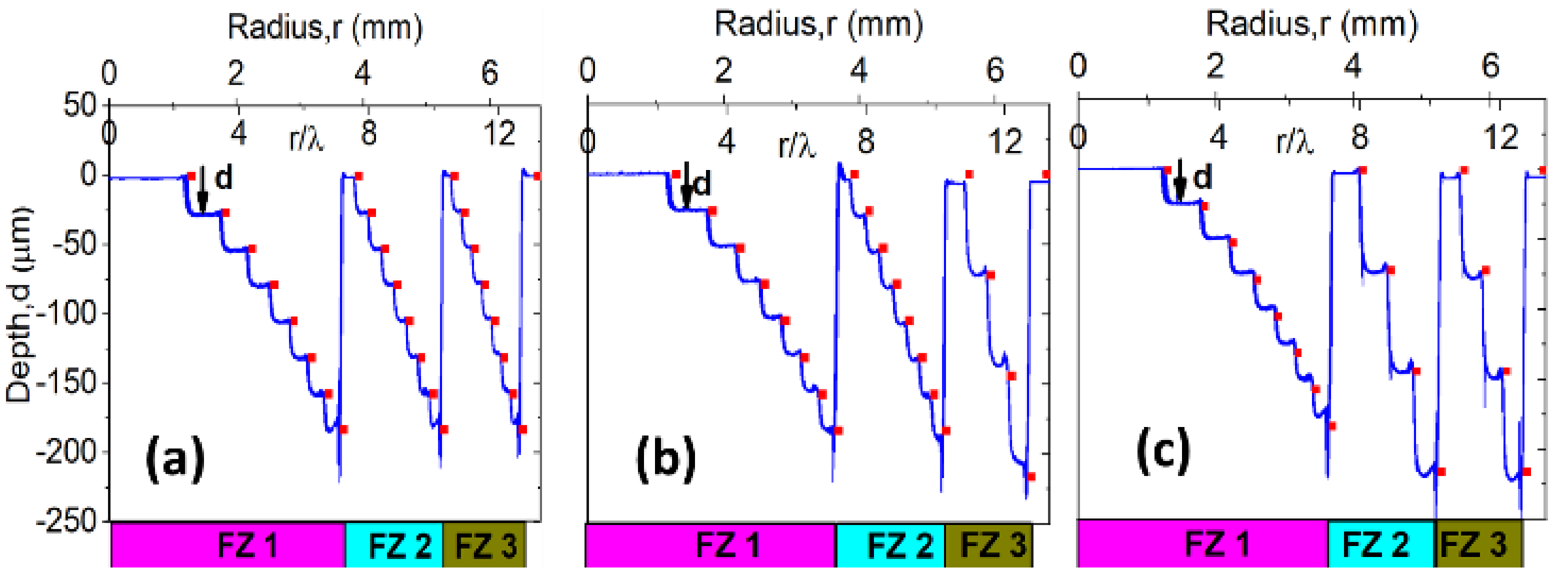

Fig. The step profile of (a) reference design MPZP with Q=8; (b) optimized H-MPZP1 with Q = 4 at the most outer sub-zones area FZ3; and (c) optimized H-MPZP2 with Q = 4 at both FZ2 and FZ3 areas.

Parameters of a loss-free Si wafer with a thickness (h) of 0.5 mm was used to design the hybrid multi-phase zone plate (H-MPZP) samples of different shape and step profiles. The standard MPZP was designed using the following equations:

$$\mathbf{r_n} = \sqrt{\frac{2\lambda\mathbf{n}\left(\mathbf{F} + \frac{\boldsymbol{d}}{2}\right)}{\mathbf{Q}} + \frac{\mathbf{n}^2\,\lambda^2}{\mathbf{Q}^2}}$$

$$\boldsymbol{d} = \frac{\boldsymbol{\lambda}}{\boldsymbol{Q}(\boldsymbol{\varepsilon} - 1)}\left(1 + \frac{\boldsymbol{m}}{8}\right)$$

S. R. Ayyagari et al., IEEE TTST (under review).

Optimization procedure

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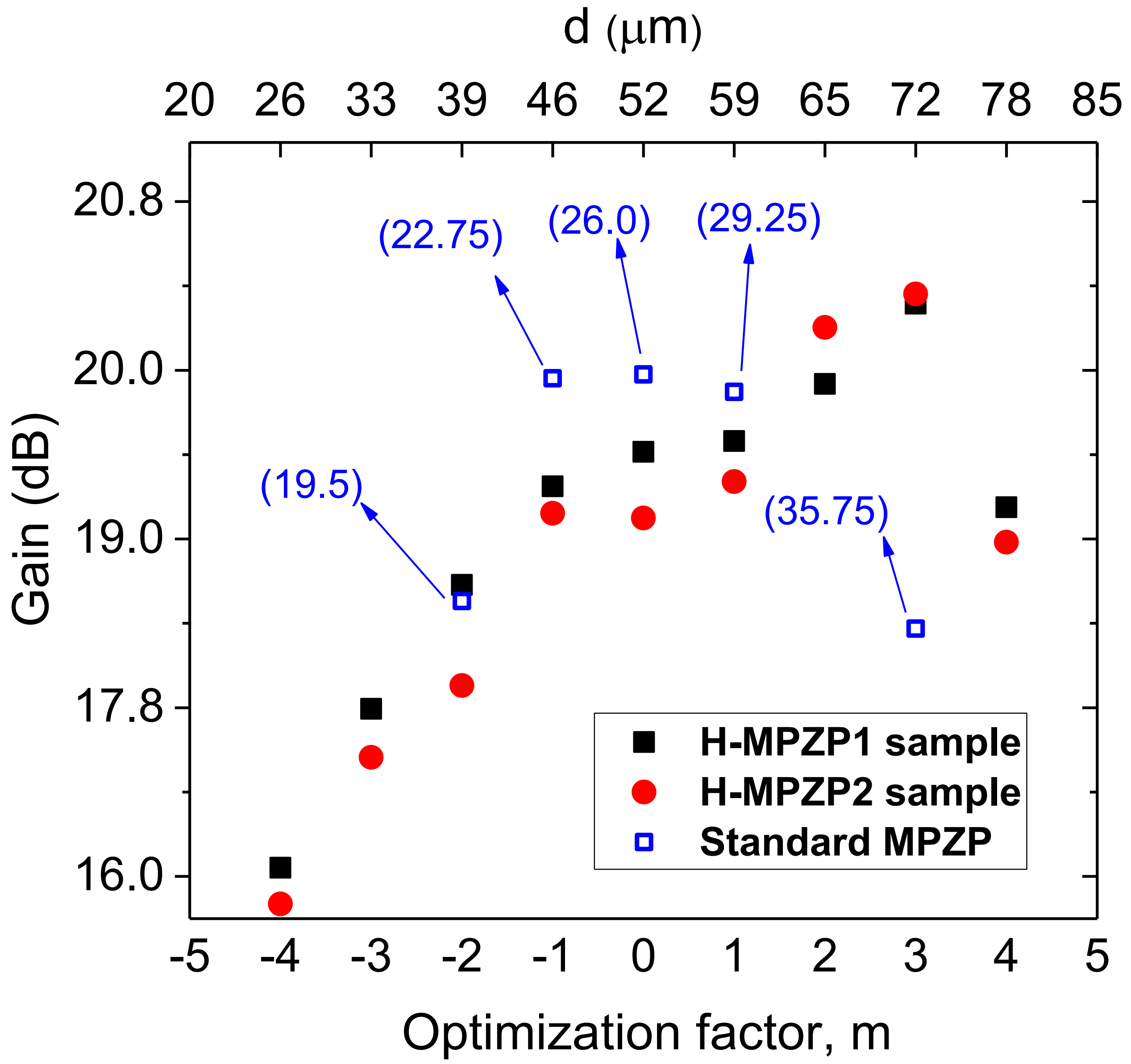
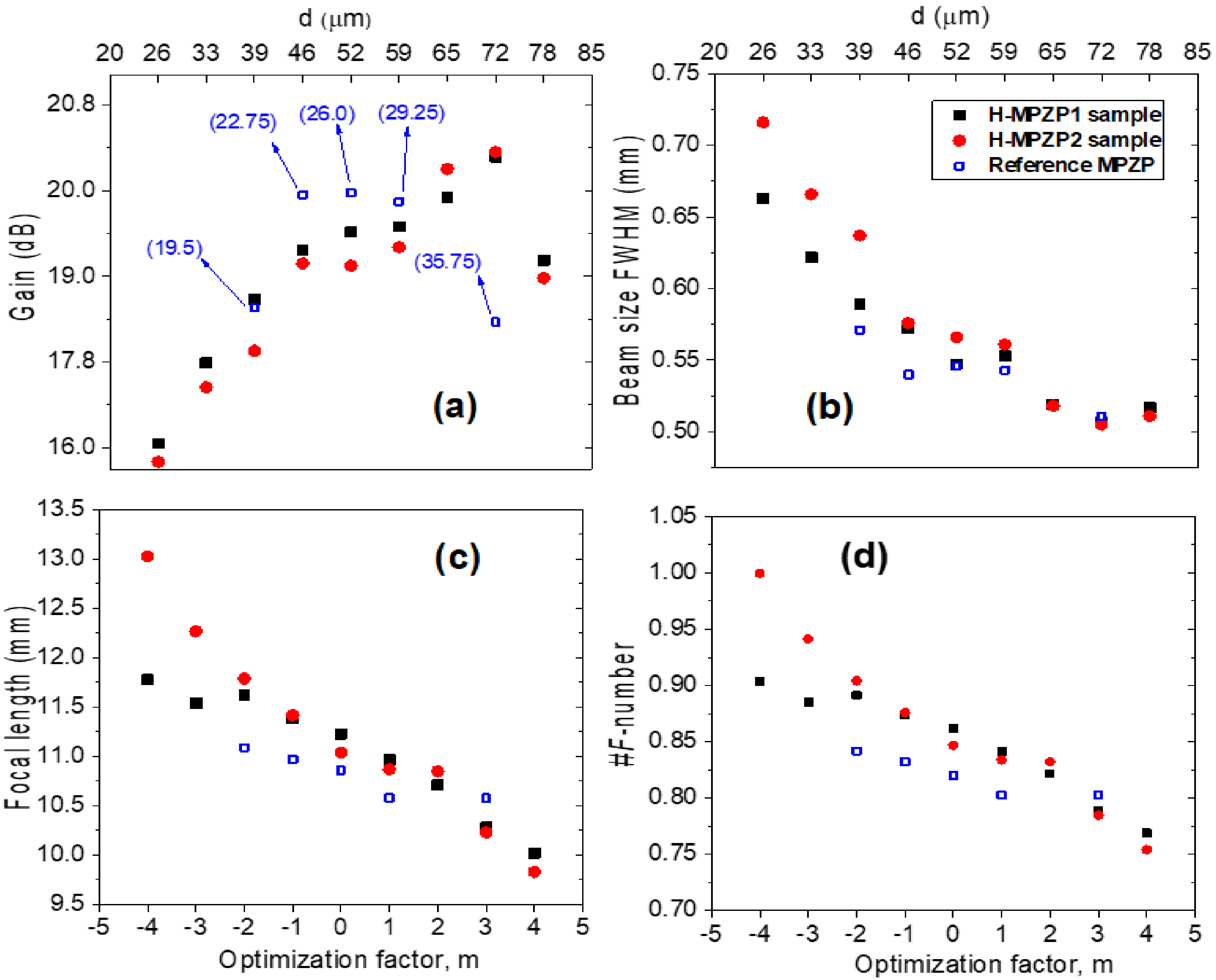


- The phase shift for the optimized phase profile (H-MPZP) samples is chosen step by step modifying the depth of subzones until the lens reaches maximum value of the focusing gain.

S. R. Ayyagari et al., IEEE TTST (under review).

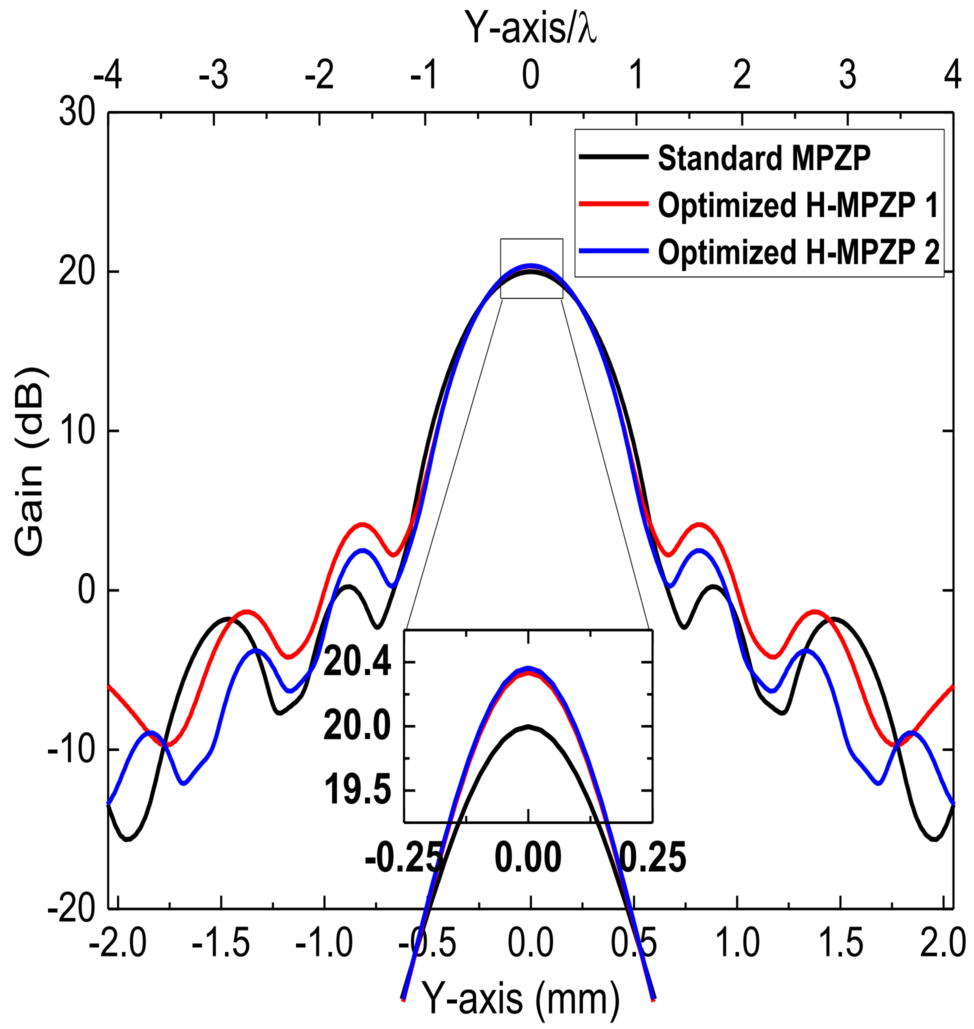
Optimization procedure



- The simulated focusing gain (a), FWHM (b), focal distance (c), and #F-number (d) of the reference MPZP, H-MPZP1 and H-MPZP2 samples with different value of the optimization factor (m), bottom X-axis, and resulting depth of subzones, d, top X-axis.

S. R. Ayyagari et al., IEEE TTST (under review).

Optimization Results

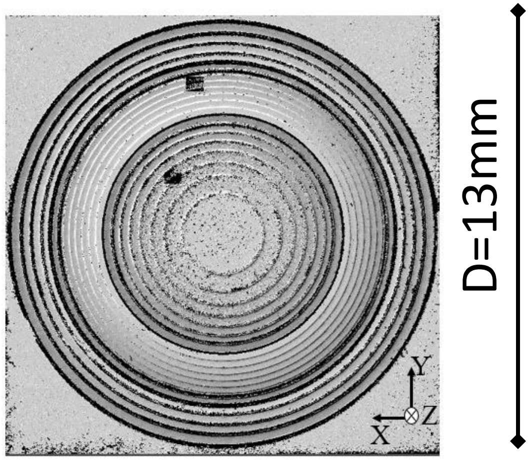


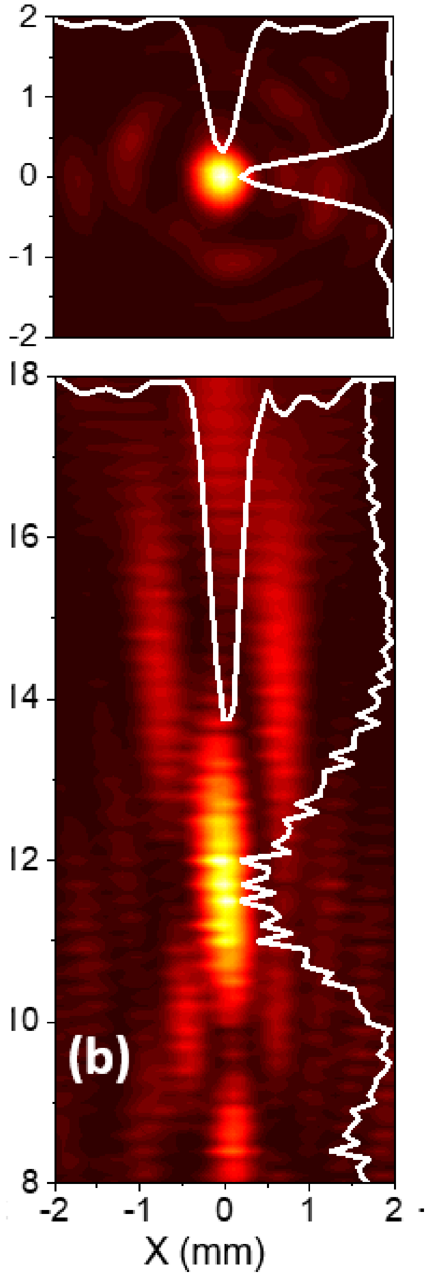
- With a precise control over phase shift with a step size of m/8 times the depth of subzone to the actual subzone depth revealing its Optimal value of +3/8, which means a incremental phase shift of π/4 for a desired wavelength with an increase of absolute focusing gain at the central beam by up to 10% (+0.4 dB).
- Change of sidelobe level from **0.23 dB** for standard MPZP to **4.05 dB** for H-MPZP1 sample. Further simplifying H-MPZP1 to H-MPZP 2 resulted in two times smaller sidelobe magnitude (**2.48 dB**).

S. R. Ayyagari et al., IEEE TTST (under review).

Experimental Validation

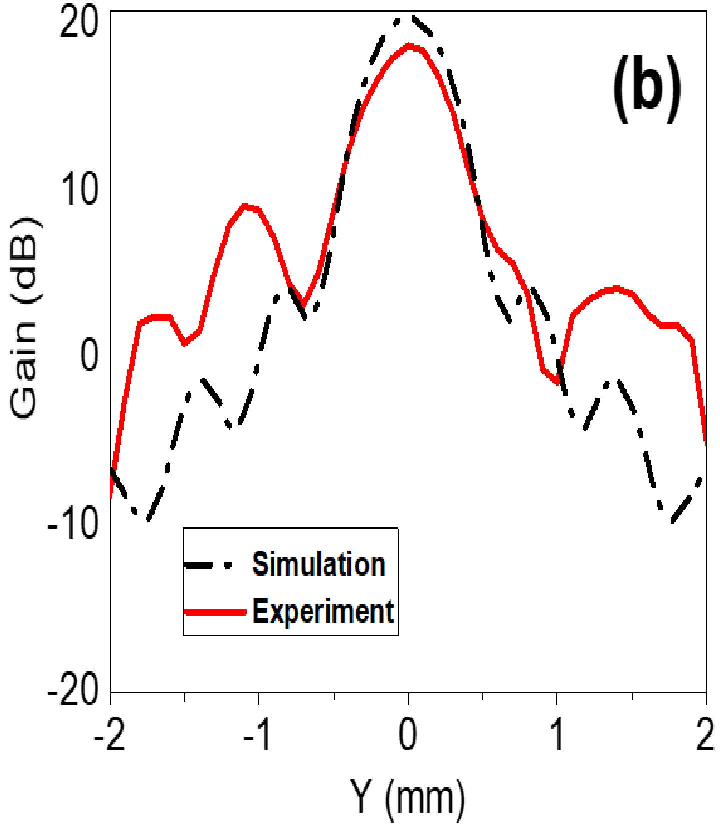
H-MPZP 1





- The zone plates were patterned on Si by Direct Laser ablation (DLA) technique.
- Focusing performance of the samples was explored experimentally using a VDI continuous wave system at 585 GHz.

- THz beam intensity distribution at the focal plane (XY plane) and along the optical axis (XZ plane) shown on top -right. And on right the focusing gain in semi-log scale obtained experimentally (solid red lines) and numerically (dot-dashed black lines) at the focal plane for the (b) Optimized H-MPZP 1.

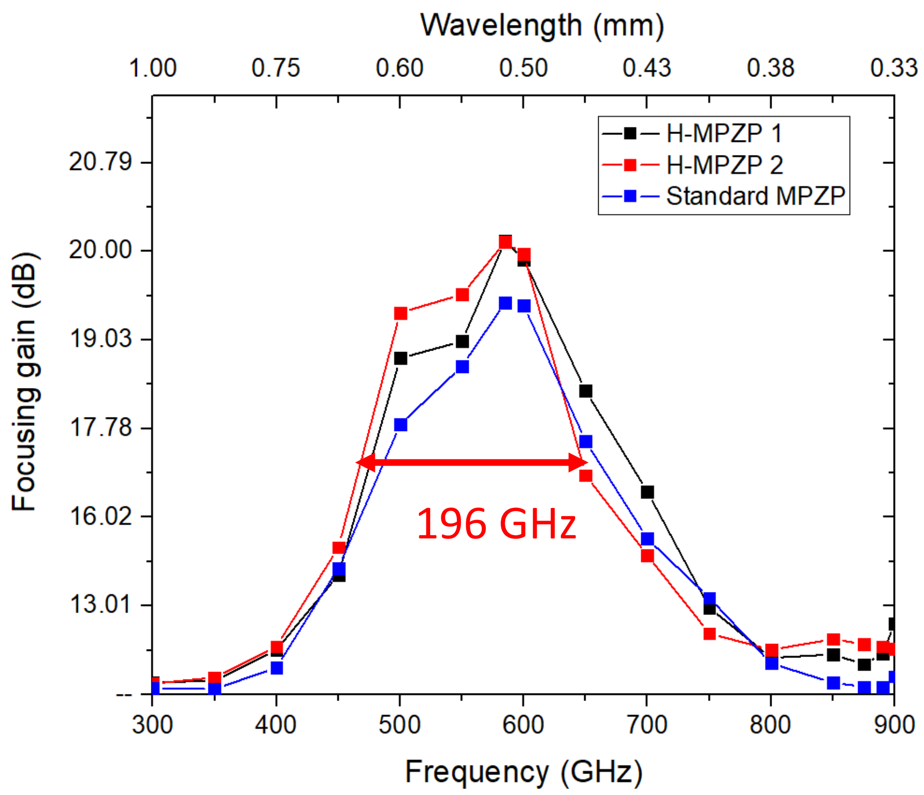


S. R. Ayyagari et al., IEEE TTST (under review).

Summary of experimental and simulation results for the MPZP samples.

Sample	Simulation		Experiment	
	FWHM (mm)	Focusing Gain (dB)	FWHM (mm)	Focusing Gain (dB)
Standard MPZP	0.548	20.0	0.498	17.9
Optimized H-MPZP 1	0.507	20.3	0.527	18.7
Optimized H-MPZP 2	0.505	20.4	0.498	18.3

Simulated Gain Bandwidth



- The feasibility to use large diameter laser beam leads to faster and less demanding fabrication process of those lenses. For example, if we consider the narrowest ring of the standard and hybrid design to be respectively of 192 μm and 345 μm, then we increase proportionally the laser spot and 1.8 times faster fabricate hybrid lens of optimized design.

Conclusions

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- We proposed hybrid Si MPZP lens development procedure which can be further modified by scaling the design to other frequencies with different zone numbers.
- The focusing gain of the H-MPZP lenses with eight and four level phase profiles was optimized by adding a phase shift of $\pi/4$ (f=585 GHz // λ=0.51 mm) to outer subzones in order to achieve similar or even up to 10% higher values as compared to the Standard MPZP lens. The increment in the focusing gain was attributed to the reduced shadowing effect and efficient constructive interference of the spherical wavefront.
- The operation bandwidth at 3dB level was found to be of about 200GHz for all lenses.

Acknowledgement

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