Phase profile optimization of silicon multi-phase zone plate lenses for operation at 585 GHz frequency

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Abstract Phase profile of the multi-phase zone plate (MPZP) was optimized for efficient lens operation at 0.585 THz frequency. Different type of the MPZP samples with a focal length of about 13 mm and a focal number of 1 were designed of high-resistivity silicon. The depth and size of initial eight step phase profile were optimized in the most outer subzone areas. Successful optimization of the phase profile allowed us to reduce manufacturing complexity and achieve higher focusing gain values in comparison to respective classical design MPZP.

Numerical Development

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 reference MPZP was designed using the following equations[1]:

$$r_n = \sqrt{\frac{2\lambda n(F+\frac{d}{2})}{Q} + \frac{n^2\lambda^2}{Q^2}} \qquad d = \frac{\lambda}{Q(\varepsilon-1)}\left(1+\frac{m}{8}\right),$$

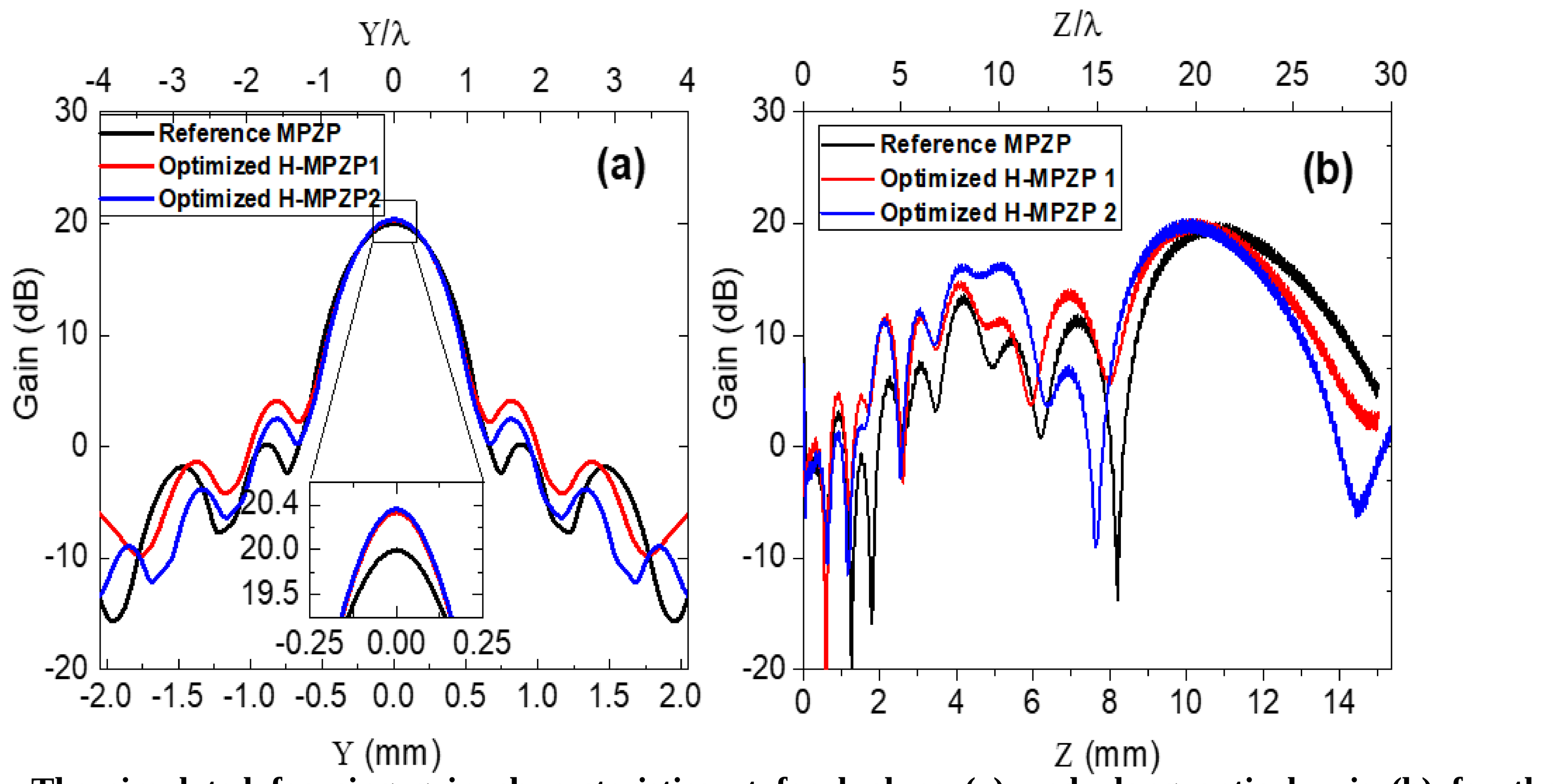


Fig.1. The simulated focusing gain characteristics at focal plane (a) and along optical axis (b) for the reference MPZP sample and two optimized H-MPZP1 and H-MPZP2 samples. The results are shown in semi-log scale, where dB = 10 log (*Gain*). Inset shows the gain characteristics of the same samples in zoomed area. Note, bottom axis is in millimeters, whereas top is normalized to the design wavelength λ.

Modeling results

The phase shift for the optimized phase profile (H-MPZP) samples is chosen step by step modifying the depth of subzones with a factor of (m/8) times the depth of subzone to the actual subzone depth, at outer Fresnel zones until the lens reaches maximum value of the focusing gain.

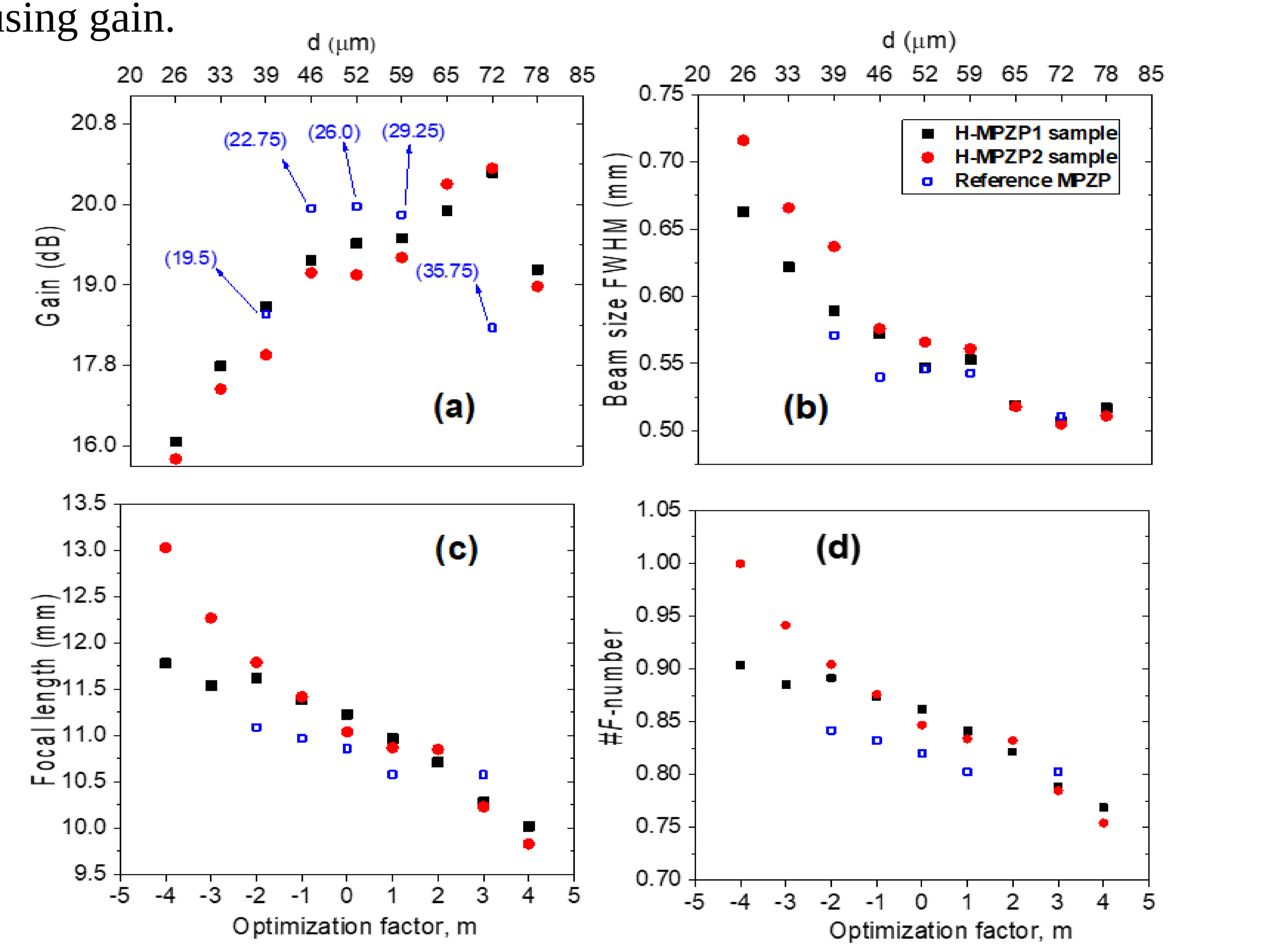


Fig.2. The simulated focusing gain (a), FWHM (b), focal distance (c), and #F-number (d) of the reference MPZP, H-MPZP1 and H-MPZP2 samples with different value of the optimization factor (m), bottom X-axis, and resulting depth of subzones, d, top X-axis. Inset numbers in brackets, which are indicated only in (a), show in micrometers the resulting subzones depth relating to the optimization factors for the reference MPZP samples.

Fabrication Procedure

The zone plates were patterned by an industrial-scale pulsed laser (Atlantic 60, EKSPLA UAB) with a pulse duration of 10 ps, operation wavelength of 1064 nm, scan speed of 856 mm/s (47% spot overlap), 32 μm laser spot size diameter, 11.8 J/cm2 laser irradiation fluence, hatch angle rotation of 45 deg after each scan and etch depth of 0.2 μm per layer which allowed to maintain precise control over the profile shape of the MPZPs. Pictures of the fabricated samples and their step profiles scanned from center towards edge side are shown below.

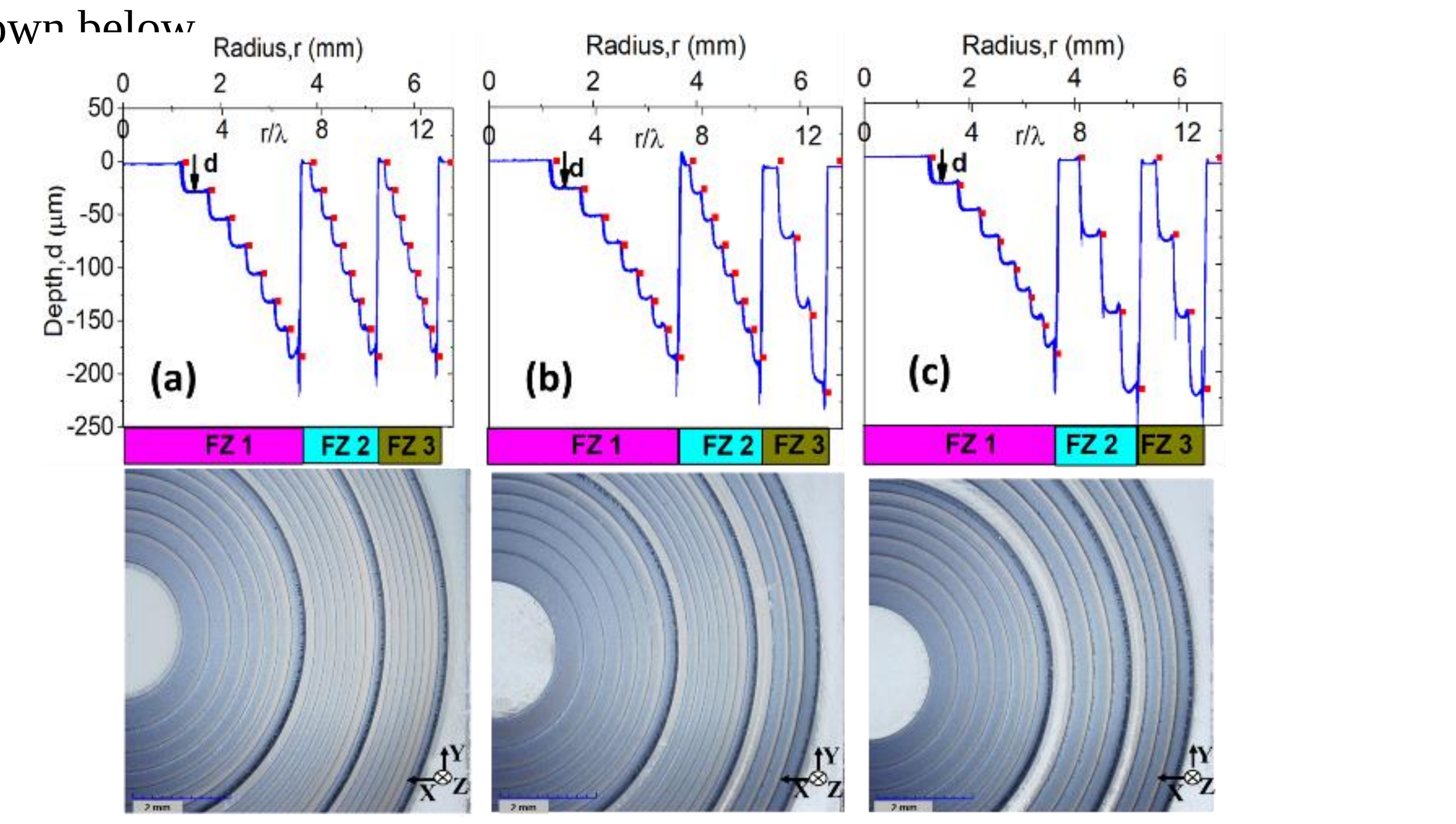
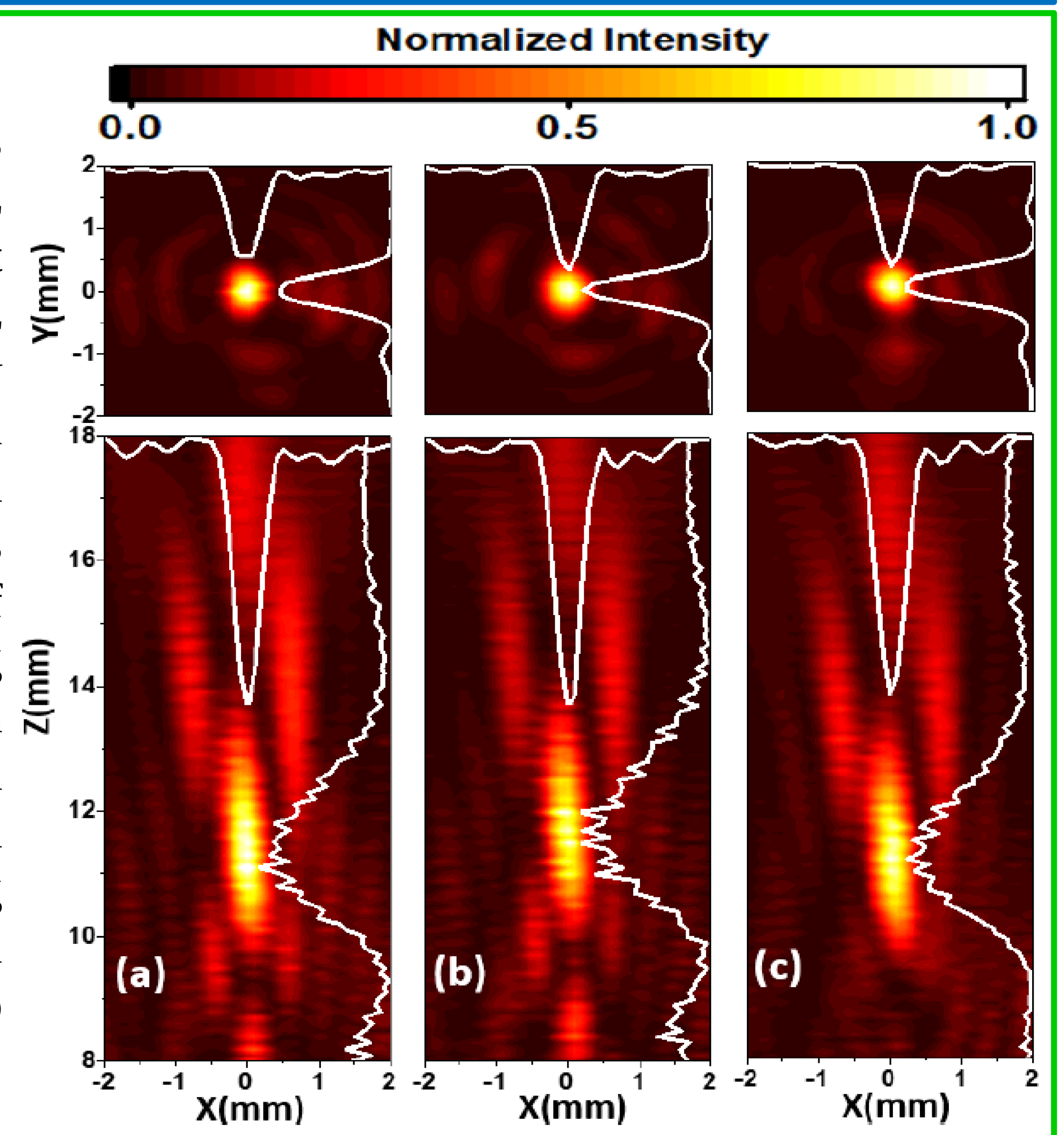


Fig.3. The profilometer measurements across centrum line (top row) and microscope picture (bottom row) of the fabricated samples of (a) reference design MPZP with Q=8; (b) optimized H-MPZP1 with Q = 4 and m = +3 at the most outer sub-zones area FZ3; and (c) optimized H-MPZP2 with Q = 4 and m = +3 at both FZ2 and FZ3 areas. Note step-profile measurements numerical design (Red dots) and "Veeco Dektak 150" profilometer (Blue line).

Experimental Validation

Focusing performance of the samples was explored experimentally using a THz continuous wave system set to operate at the frequency of 585 GHz. The 585 GHz frequency radiation generated by Schottky diode-based AMC (Amplification Multiplication Chain) outcoupled via horn antenna was collimated using HDPE lens to measure the focusing performance of MPZP samples. The THz beam outgoing from the sample was evaluated with microbolometer detector which was placed on an automated 3D scanning stage system to measure the intensity distribution along the optical axis (Z-axis) and in the focal plane (X- and Y- directions) in respect to the MPZP sample.



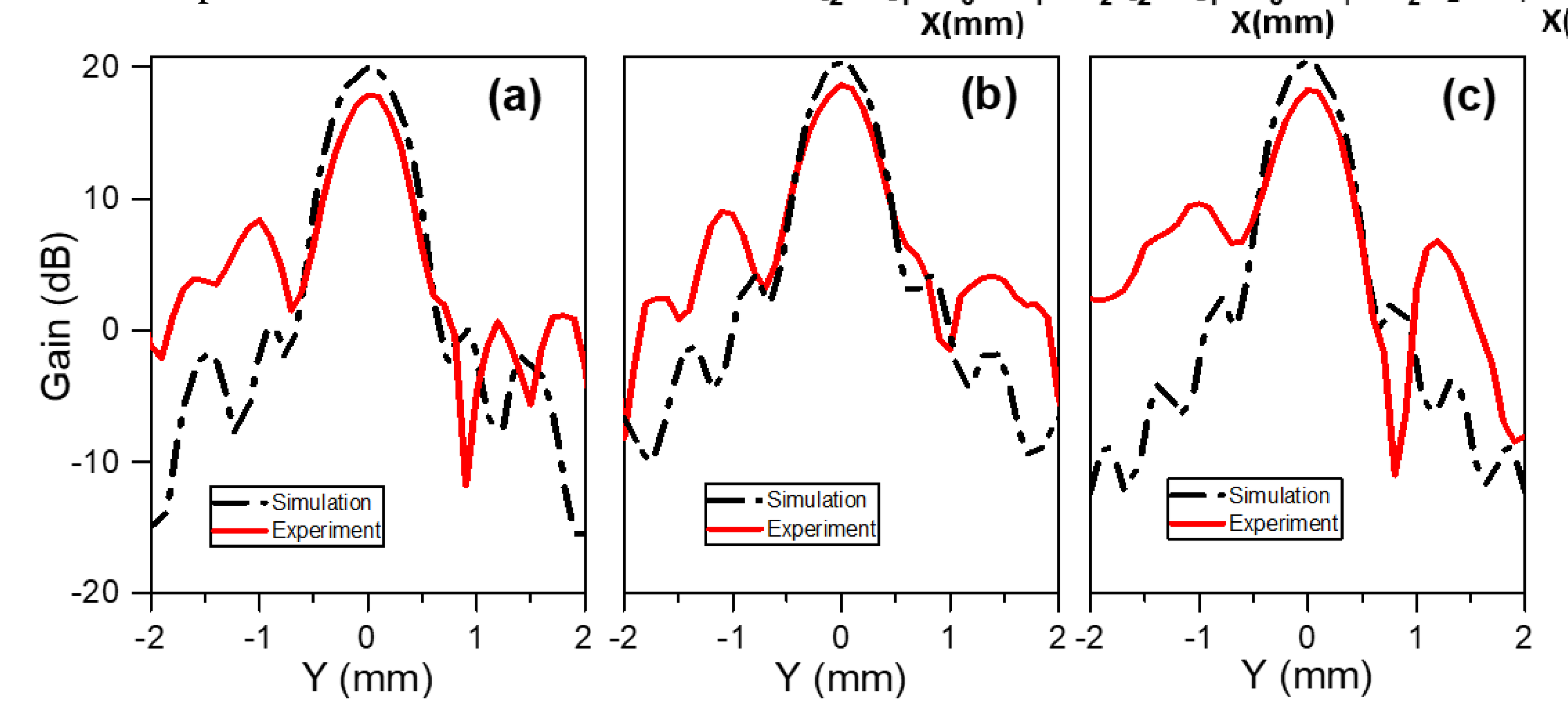


Fig.4. Measured THz beam intensity distribution at the focal plane (XY plane) and along the optical axis (XZ plane) shown on top -right. And on bottom the focusing gain in semi-log scale obtained experimentally (solid red lines) and numerically (dot-dashed black lines) at the focal plane for the (a) Reference MPZP, (b) Optimized H-MPZP 1 and (c) Optimized H-MPZP 2 samples

Conclusions and Future work

The H-MPZPs with mixture of eight and four level phase profiles have been developed for frequency of 585GHz. The focusing gain of such H-MPZPs was similar or even up to 10% higher as compared to the reference MPZP of standard design. The increment in the focusing gain was attributed to the reduced shadowing effect and efficient constructive interference of the spherical wavefront because of precise control over the phase shift of incoming radiation [2,3]. Furthermore, we introduced new approach to build much simpler and less complex diffractive optical elements which can be integrated on semiconductor chips with THz detectors and emitters. In the next step, we are going to implement on-chip integrated solutions for such H-MPZPs with GaN/AlGaN HEMTs (high-electron-mobility transistors) based THz devices with aim to improve the signal to noise ratio of THz imaging systems.

References

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