國立清華大學 電機工程學系

實作專題研究成果報告

Designing and 3D Printing Customised Phase Plates based on Modified Gerchberg-Saxton Algorithm

Major Category: Optoelectronics (光電領域)

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Abstract

The advancement of optical systems heavily relies on the precision and adaptability of phase control devices, such as phase plates, which are able to modulate light to achieve the desired wavefront transformation. This research introduces an approach to designing phase plates using the Gerchberg-Saxton algorithm, a computational technique used for phase profile retrieval. We adapted the algorithm using the Huygens principle to optimize phase profiles for terahertz wave modulation.

Using Python for simulation, the design process involved iteratively adjusting the phase distribution, wherein each iteration refined the structure depending on the Huygens principle GS-algorithm computation phase errors within the simulated output and the desired distribution pattern. Utilizing commercial 3D printing machines, the phase plates were fabricated from polymer materials, a material chosen for its favorable optical properties at terahertz frequencies.

Computational simulation aligned with the experimental results demonstrate that the generated 3D-printed phase plates achieve a significant convergence similar to the desired distribution pattern. Yet, the need for additional adjustments will still be needed to perfect the design. This initial success validates the adaptability of the algorithm and highlights the potential of this approach in practical optoelectronic device fabrication

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I. Introduction

In recent years, the manipulation of terahertz (THz) waves has emerged as an area of research, driven by the potential in nondestructive testing, security screenings, and medical diagnostics. One of the challenges in THz applications is the efficiency and control of the beam profiles, which are essential to its performance. This study focuses on the innovative design of a phase plate that can modulate THz waves to achieve the desired distribution pattern.

Motivation and Purpose: The motivation behind this research is to enhance the control over THz beam shaping using computational algorithms, which is more conventional and practical. The purpose of this study is to design, simulate, and fabricate THz phase plates using a modified Gerchberg-Saxton algorithm that allows accurate manipulation of the beam profiles, which can help the effectiveness of various THz applications. Also, this study is made as a requirement for the researcher course in Special Topic on Implementation System.

This research and study builds on previous studies that have been made, such as Gospodaric et al. (2018), which have demonstrated the potential of diffractive optical elements in shaping THz beams, where some also used a modified GS algorithm in the phase profile design. The use of 3D printing technology, which can be more accessible, for fabricating a phase plate offers a promising idea for rapid prototyping and testing of complex optical devices.

The Gerchberg-Saxton algorithm, which is commonly used in optical phase retrieval, provides a robust method for designing phase plates. Starting from the initialization of the phase by setting it as a flat surface or having an initial random guess of the phase. Continue with a set number of iterations for forward propagation, amplitude enforcing, and backward propagation.

However, its common application in THz waves has been limited. By integrating the Huygens Principle, the focus of this paper, into the algorithm, it allows more adaptation towards THz wave application, addressing the nature of THz wave and its diffraction with different materials.

Huygens principle is a fundamental concept in wave theory that describes how waves propagate. According to this principle, every point on a wavefront acts as a source of tiny spherical wavelets, which spread out in the forward direction at the speed of the wave itself. After a small interval, the new position of the wavefront is defined as the surface tangential to these wavelets. Making it suitable to address the character of the THz wave.

Innovation: This study introduces an innovative adaptation of the Gerchberg-Saxton algorithm, incorporating the Huygens principle to optimize it for Thz beam shaping using a conventional and mostly known programming language, *Python*. Furthermore, it also makes use of 3D printing for creating THz optical components, combining the convenience of the design simulation with the ease of fabricating such elements.

The key research question addressed by this is: How can the Gerchberg-Saxton algorithm be effectively adapted to design THz phase plates that achieve a set desired intensity output beam profile? The solution approach involves modifying the algorithm to accommodate the nature of THz wave and employing 3D printing technology to fabricate the designed phase plates. All computational design, calculation, and simulation were performed using *Python*, taking advantage of its libraries for numerical and scientific computing.

All the design of the algorithm was built by the researcher and his assigned mentor, Seyed Mostafa Latifi, using *Python*. Including the implementation of the modified Gerchberg-Saxton algorithm using the Huygens principle and the simulation of the expected beam profiles. The 3D printing of the acquired phase plates was printed in the lab, following the profile from the computational model results.

II. Research Methodology

To design and fabricate the phase plates, we are using the Gerchberg-Saxton algorithm built using the *Python* language, specifically making use of the Jupyter Notebook. Initially, the original GS algorithm employed for optical phase retrieval was modified to suit THz wave modulation. This modification involved theoretical adjustments to integrate the Huygens principle, ensuring the algorithm would handle the propagation characteristics of THz waves.

$$E^d_{(x,y)}(x',y') = \frac{A_{(x,y)}}{r_{(x,y),(x',y')}} exp[-ikr_{(x,y),(x',y')} + i\phi].$$

$$E^i_{(x',y')} \propto \sum_{(x,y)} E^d_{(x,y)}(x',y')(1+cos\Omega)$$

Using the above formulas to calculate each point (x, y) in the diffraction plane, which is a source of a spherical wave contributing to the electric field in the image plane at the point (x',y'). Where $r_{(x,y),(x',y')}$ is the distance between the point (x, y) and the point (x',y'), $\boldsymbol{k}$ is the wave number, $A_{(x,y)}$ is the amplitude of the wave, and ф phase of the wave based on the point (x, y). After calculating in each point (x, y), next is to sum it all up with the addition of (1 + cos Ω), where Ω represents the angle between the system's optical axis and the line that connects the points (x, y) and (x',y').

To have an accurate initial beam input intensity, so that the calculation highly represents the real practice. A formula to represent near-Gaussian distribution is used.

$$E(x,y) \propto \frac{1}{2\pi\omega^2} exp[-\frac{x^2+y^2}{4\omega^2} + \frac{2i\pi}{\lambda}(\sqrt{l^2+x^2+y^2} - l)]$$

Here, l is the distance between the output beam and the phase plate; for the simulation, it is set to 75 mm. A beam width of 80 mm and 200 GHz was also set following the equipment that is available in the lab. With this initial input, a simulation and calculation are done using the algorithm, trying to recreate 2 different target images in order to observe the capability of the algorithm in different desired output intensities.

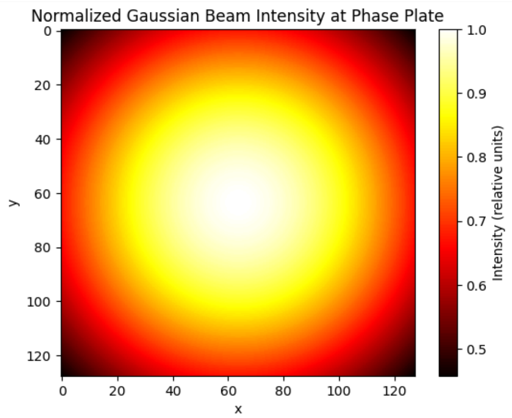

Fig. 1. A near-gaussian distribution formula is used to best represent the input source for the simulation, and normalization is done to the intensity for more stabilized calculation (x and y are the amount of grid)

In each simulation, 128 grid sizes are used to ensure the high quality and accuracy of the calculation and dimension of 100x100 mm for both the phase plate and the target image plane. The set distance between the diffraction plane and the image plane is set to 50 cm.

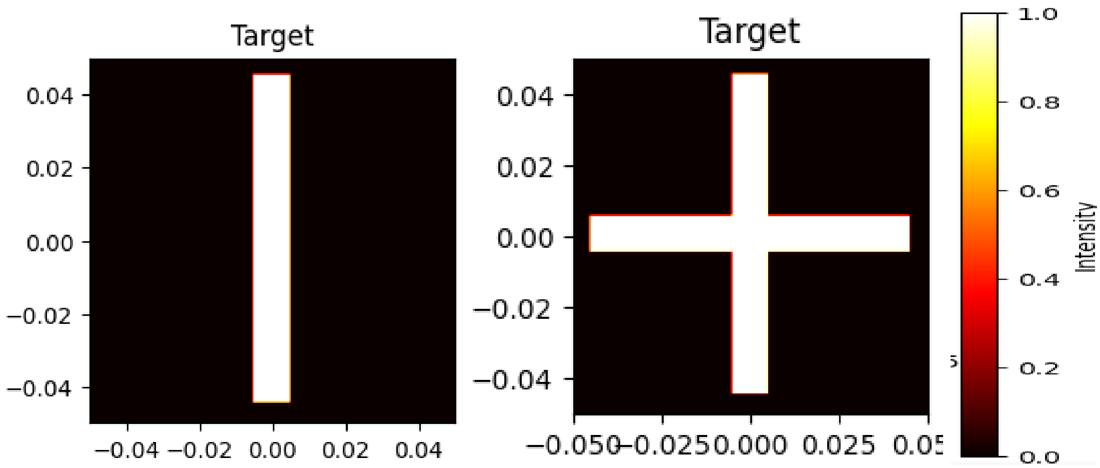

Fig. 2. Two target desired output intensity are set with a vertical line shape and plus shape with a plate dimension of 100x100 mm (x and y grid is in meters)

With the parameter set, the algorithm is run for 100 iterations for each target desired output intensity, which took around 3 hours of run time in a commercial computer. With the phase distribution retrieved from the modified GS algorithm, another formula is introduced to allow the fabrication of the phase plate.

$$z(x,y) = \frac{\phi(x,y)\lambda}{2\pi(n-1)}$$

Here, n is the refractive index of the polymer materials that are used for the fabrication; n = 1.7 following the equipment available in the lab. With the above formula, the thickness of the acquired phase profile can be calculated to later be used for the fabrication inside the 3D printer for the experimental evaluation.

For the experimental evaluation, the acquired thickness of the phase plate is used to generate an STL so it is able to be printed using the 3D printer available in the lab. 2

of the acquired phase plate for plus and vertical line is able to be printed with the help of Dennis 吳劭軒 in operating the 3D printer. After printing, the testing can be done.

III. Experimental Results

Running the algorithm for 100 iterations, the algorithm has also been modified so that in each iteration it can be observed whether the results are converging or not. The results of the phase profile from the simulation are below:

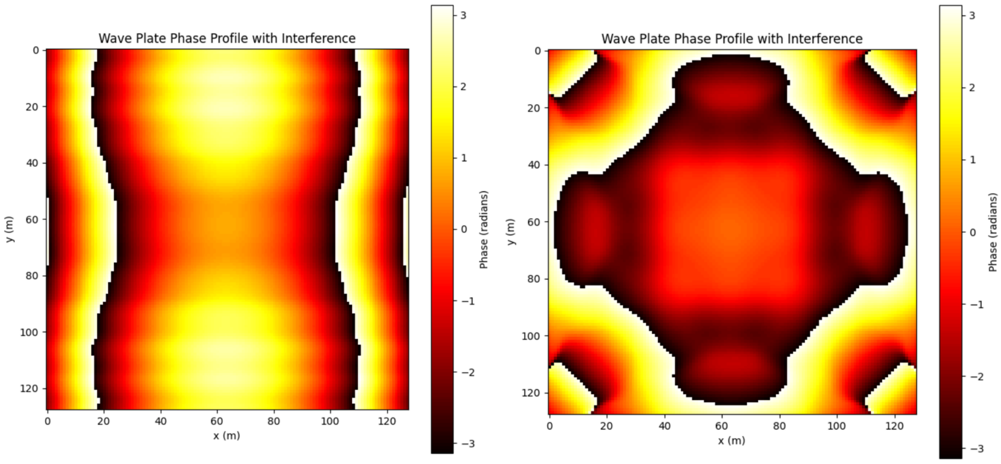

Fig. 3. Phase profile after going 100 iterations for both vertical line (left) and plus-shaped (right) target output intensity

After acquiring the phase profile for both desired output intensities, then the fabrication of the phase plate can also be done to check if the calculated phase plate can be used in the real-world scenario and not just in simulation or calculation. For the fabrication, 2 STL files are generated for both phase plates with dimensions of *100x100 mm* and *1.67 mm* in max thickness. Now, to check if the output intensity that is generated by the phase plate is accurate or not, another simulation is done.

The generated intensity produced for both target intensities can be seen below:

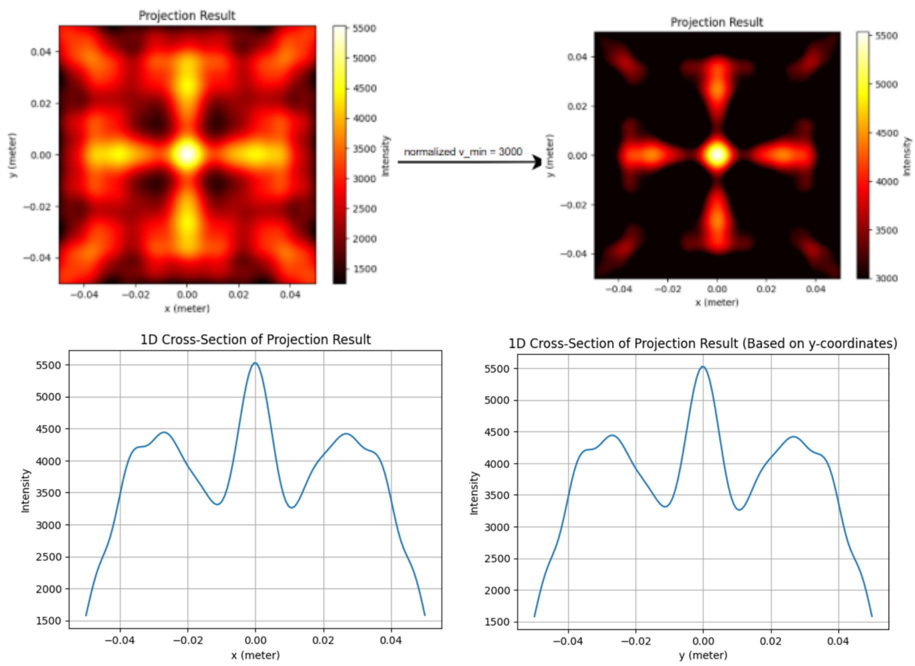

Fig. 3. GS algorithm results for plus-shaped desired output intensity

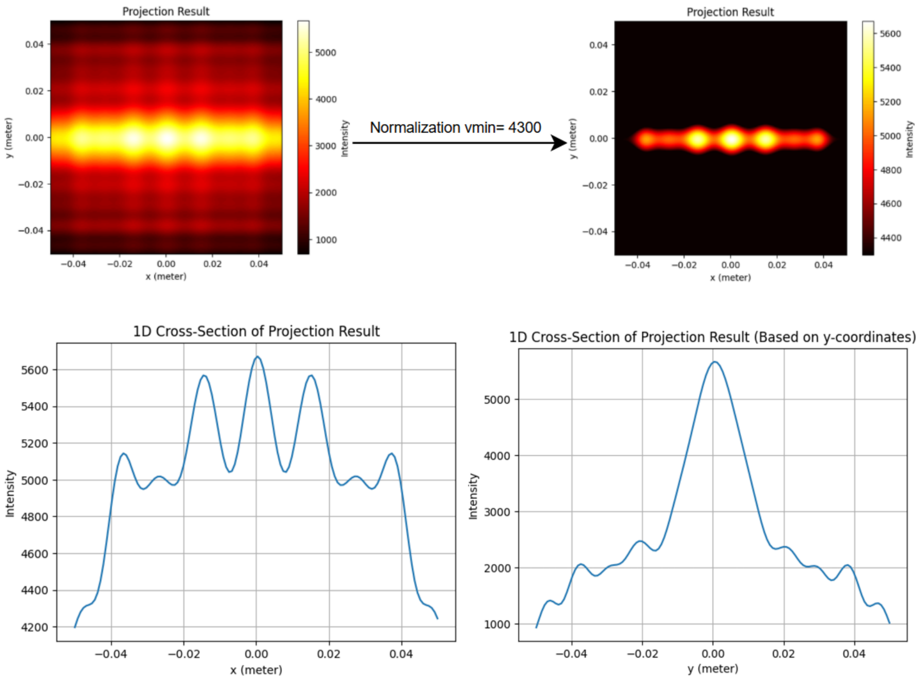

Fig. 4. GS algorithm results for Vertical line desired output intensity

From the above results, both generated phases are able to generate an output intensity that is close to our initial target output intensity. Meaning that our algorithm is converging. However, some adjustment can still be made since the generated output intensity is still not perfect.

An obvious adjustment that can be made is that how to plot the image, from the generated output intensity of the vertical line, it failed to converge into a vertical line instead it is generating a horizontal line, giving a sign that there is some mistake on how to handle the image plotting.

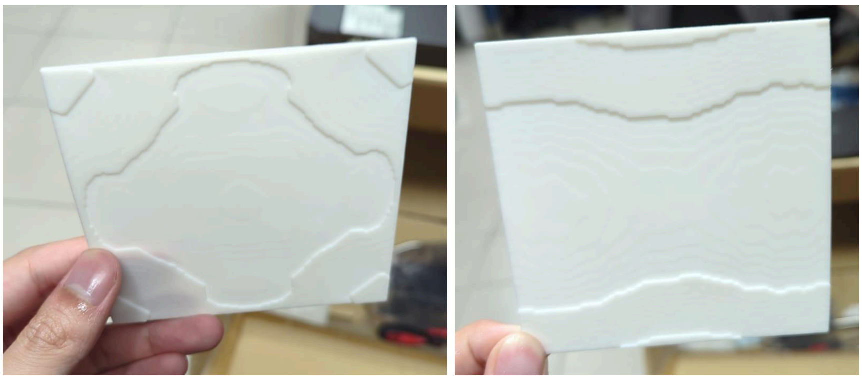

Fig. 5. GS algorithm results for Vertical line desired output intensity

IV. Conclusion

This research successfully demonstrates the application of a modified Gerchberg-Saxton algorithm, integrated with the Huygens principle, for designing phase plates to shape terahertz (THz) wave beam profiles. The approach involves computational simulation, iterative refinement of the phase profile, and subsequent fabrication using 3D printing technology. The experimental results align closely with the target output intensities, validating the algorithm's effectiveness and convergence capability.

However, real-world testing of the fabricated phase plates was not performed due to time constraints. Such testing would provide a critical evaluation of the phase plates' performance and verify whether the algorithm-generated profiles translate effectively into practical applications. Addressing this in future work will be essential to confirm the robustness of the algorithm and its suitability for real-world THz wave modulation. Nonetheless, this study provides a strong foundation for integrating computational design with fabrication, contributing significantly to advancements in optoelectronic devices.

V. Reference

Anderson, F. L. (2021, October 12). *Huygens' Principle geometric derivation and elimination of the wake and backward wave*. Huygens' Principle: geometric derivation and elimination of the wake and backward wave | Scientific Report. Retrieved October 21, 2024, from https://www.nature.com/articles/s41598-021-99049-7#:~:text=Huygens'%20Principle%20(1678)%20implies,to%20all%20the%20secondary%20wavelets

Dzhirkirba, K. R., Gusikhin, P. A., Murav'ev, V. M., Kukushkin, I. V., Gospodaric, J., & Pimenov, A. (2022, April). 3D-PRINTED PHASE WAVE PLATES FOR CREATION OF TERAHERTZ BEAMS WITH LINEAR POWER DISTRIBUTION. *Radiophysics and Quantum Electronics*, *65(4), 10.1007/s11141-023-10212-8*

Gospodaric, J., Kuzmenko, A., Pimenov, A., Huber, C., Suess, D., Rotter, S., & Pimenov, A. (2018). 3D-printed phase waveplates for THz beam shaping. *Applied Physics Letters*, *112*(221104), -. 10.1063/1.5027179

Reichel, S., Petzoid, U., Biertuempfel, R., & Vogt, H. (2009, February 19). Flat-hat glass diffractive optical beam shaper. *Proceedings of SPIE*, *7194(-), 10.1117/12.807932*

Ye, X., Xiang, F., You, C. W., Wang, K., Yang, Z., Liu, J., & Wang, S. L. (2018). Generation of a terahertz collimated top-hat beam by using two thin diffractive phase plates. *OSA CONTINUUM*, *1(4),*

VI. Plan Management and Teamwork

All of the work done for the research is done individually by the author, with the assistance of assigned mentor Seyed and other lab members. Help was also received from Professor Yang by giving feedback and insights on doing the research. Moreover, the progress that is done here is also with the facilities that are given from the Yang Research Group lab.

I've learned many things in doing this research, and in the moment of writing this report, the research can be continued by doing the testing with the fabricated phase plate. So, after submitting the report, the research will still be continue.

The workflow of this research was started by picking up and understanding all of the main ideas of the Gerchberg-Saxton algorithm, Huygens principle, and phase plate design. After a good understanding of the topic of the research, the construction of the algorithm is started.