Phase Reconstruction of the LG Mode Using Photonic Crystal Fibre and the Gerchberg-Saxton Algorithm for Cyber Security

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Abstract

Optical encryption has the capability of improving data security and assurance. This is achieved through the use of modified Gerchberg-Saxton algorithm in photonic crystal fiber based communication systems. Photonic crystal fiber (PCF) is used as a powerful waveguide due to its selective mode excitation capabilities as well as its effective mode confinement ability. The Gerchberg Saxton (GS), is a phase retrieval iterative algorithm that systematically solves the general amplitude-phase-retrieval problem in any linear unitary or no unitary transform system. In this paper, the GS will be used for mode conversion from one source mode and reconstructed to four target modes all generated through a PCF in the Fourier domain. The results indicate that the GS accurately converts the target modes from the source mode and this can be applied in cryptography for cyber security and switching.

Keywords –Gerchberg Saxton, mode conversion, mode division multiplexing, cybersecurity

I. Introduction

When we talk of current trends that happen in the world we tend to classify them into normal trends and mega trends. Data communications is a mega trend that is leaning towards quantum computing. There is therefore an urgent need to research on ways to complement this technological revolution and future proof for when legacy infrastructure will be slowly phased out making way for all optical and quantum computing. As a result these huge volumes of data as well as bandwidth that will be produced will need to be secured as hackers and other cyber criminals become more sophisticated. The need to employ robust and sophisticated algorithms will arise in order to circumvent future attacks and as R&D dictates, the search continues for a future encryption mechanism that will fulfill these demands.

The problem in summary becomes the lack of enough encryption mechanisms for the future that will safeguard optical and quantum data as it moves through the data communications and telecommunications channels from sender to receiver through data centers. Developing nations are currently investing heavily on technology infrastructure as information and communication technologies are regarded as the pillar for economic growth. Digitalisation of processes for both government and the private sector has resulted in the need for a reliable and efficient communication infrastructure. However, today's communication infrastructure requires efficient and reliable data security systems. Hence, the use of optical encryption and optimized phase retrieval algorithms has resulted in high-density storage, high speed, large fault tolerance, and anti-peeping [0,1]. Efficient mode conversion is possible using the Gerchberg Saxton (GS) algorithm through its iterative phase retrieval method where systematic iterations enable the correction of optical aberrations [1]. The Gerchberg-Saxton algorithm is an iterative algorithm [2, 3]for retrieving the phase [2-5]of a pair of light distributions or any other mathematically valid distribution related via a propagating function, such as the Fourier transform[6], of their intensities at their respective optical planes are known. It is often important to know only the phase distribution from one of the planes, since the phase distribution on the other plane can be obtained by performing a Fourier transform on the plane whose phase is known.

Photonic crystal fiber(PCF) is imperative for next generation optical systems [7, 8]because the fiber has a transmission gap that extends far off into the infrared (IR) spectral region, these fibers are also able to exhibit a very small core diameter and this enables nonlinear[9] active optical functions such as [10]super continuum generation in the mid-IR and optical gates. PCF allows the signal to be more filtered[11] and spectrally efficient and enable it to cater for longer distances with more capacity. High bandwidth creates new ways to exploit many new types of services.

These services better our quality of life, and also give more revenue streams for telecoms operators keeping the cost affordable for basic communications services. With regards to mode conversion, because of its capability to confine light[12] with changes to the size of holes, distance between the holes as shown in Fig.1, arrangement of holes and size of the core[7], consequently altering the refractive index of the core to be higher than that of the surrounding fiber, PCF is important in selective mode excitation.

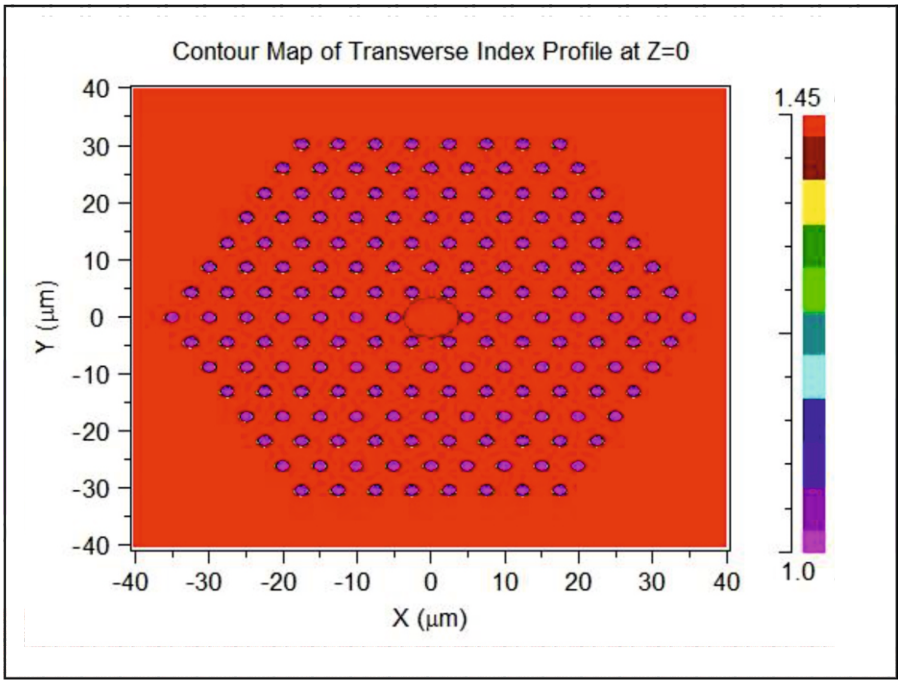


Fig. 1 Transverse Index profile of hexagonal solid core photonic crystal fiber (PCF) used to excite the LG modes that will be reconstructed by the GS Algorithm

Photonic crystal fiber is a new class of optical waveguides [13]with the help of its remarkable properties comprising a high-index core region and a surrounding silica or air photonic crystal cladding with special guiding properties that make it evade bending losses, and dispersion limitations[14-16]. These unique properties share common features with conventional optical fibers which include total internal reflection (TIR)[17]. Optical fibers and integrated optical waveguides are today finding wide use in areas covering telecommunications[18], sensor technology[19], spectroscopy[20], and medicine[21]. Their operation usually relies on light being guided by the physical mechanism known as total internal reflection, or index guiding. In order to achieve this a higher refractive index of the core compared to the surrounding media is required. Fig.1 illustrates the hexagonal structure with seven rings made of air holes with a refractive index of 1.The core, which lies on the background index, has a higher refractive index of 1.45 facilitating the confinement of the modes in the photonic crystal fiber. Each ring has a uniform air hole diameter of 1.875µm and pitch Λ which is the distance between the holes is set to 5µm. This structure was simulated and designed using the RSoft Beam Propagation platform.

II. Literature Review

Cryptography for Cyber Security and Switching

Cryptography plays a crucial role in both cybersecurity and switching to ensure the confidentiality, integrity, and authenticity of data, and this paper gives an overview of how cryptography is relevant in these contexts:

- **Cybersecurity:**
- **Confidentiality:** Cryptography helps in keeping sensitive information confidential by encrypting it. Encryption converts plaintext data into ciphertext using algorithms and keys, making it challenging for unauthorized entities to access or understand the original data.
- **Integrity:** Cryptographic hash functions are used to generate fixed-size hash values or checksums for data. Any alteration in the data, intentional or accidental, will result in a different hash value, allowing for the detection of tampering and ensuring data integrity.
- **Authentication:** Cryptography is employed in authentication protocols, such as digital signatures and certificates, to verify the identity of parties involved in communication. This ensures that the sender or receiver of information is who they claim to be.
- **Secure Communication:** Secure communication protocols like SSL/TLS use cryptographic techniques to establish encrypted connections between clients and servers. This ensures that data exchanged between them is protected from eavesdropping and tampering.
- **Key Management:** Proper key management is vital in cryptography. Secure generation, distribution, storage, and rotation of cryptographic keys are essential to maintaining the security of encrypted data.

Switching:

- **Network Security:** Cryptography is utilized to secure data as it travels across networks. This is crucial in preventing unauthorized access or eavesdropping on sensitive information during transmission.
- **VPN (Virtual Private Network):** VPNs use cryptographic protocols to create a secure and encrypted tunnel for data to traverse over a public network. This ensures that communication between connected devices is private and secure.

- **Secure Shell (SSH):** SSH uses cryptographic techniques to provide a secure channel over an unsecured network. It is commonly used for remote access to servers, allowing for secure command-line or file transfer operations.
- **Switch Security:** Cryptographic techniques are also employed in securing switch configurations and management traffic. This helps prevent unauthorized access and tampering of switch settings.

In summary, advanced cryptographic techniques and secure communication protocols have theoretical foundations in mathematical optimization, which is the basis for the GerchbergSaxton (GS) algorithm, which is primarily used in the field of optics for phase retrieval, image reconstruction, and wavefront sensing, and cryptography is a fundamental component of both cybersecurity and switching, providing the necessary tools to protect data, ensure secure communication, and authenticate users and devices in various network environments.

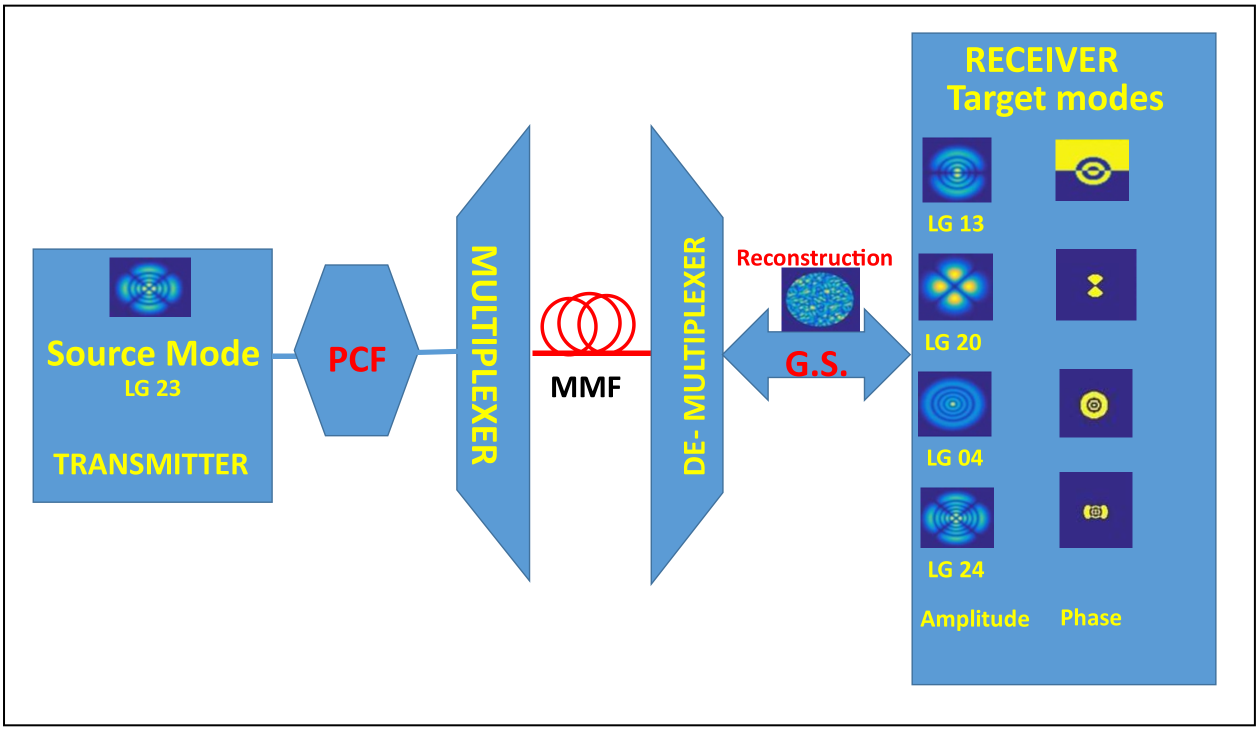


Fig. 2 Schematic diagram of mode conversion from source to target modes through the MDM system.

Mode division multiplexing (MDM) is a new multiplexing scheme that is meant to compliment the already existing multiplexing schemes. MDM is synonymous with space division multiplexing (SDM) [22]. The other existing multiplexing schemes to name but a few, are frequency division multiplexing (FDM), time division multiplexing (TDM) and WDM are the work horses of current telecommunications and data communications providers accommodating the exponential data traffic growth. To date the most commonly used multiplexing schemes are wavelength base d.

Techniques [23][24][25] and [26] are WDM based and are being used for multiplexing in current transmission schemes. Multiplexing schemes work in conjunction with each other in order to increase the number of channels in a communications system [27]. In this paper multiplexing schemes work to channel different modes in the same channel to effect mode conversion, Fig. 2, and mode shaping. Mode division multiplexing is effected solely because multimode fiber is used as the transmission medium which orthogonally transmits different modes in a spatial distribution.

III. Methodology

Simulation experiments composed the entirety of this study using Rsoft CAD simulation software called Optsim. Beamprop whose interface is a component in Optsim was also employed in conjuction with Matlab. Matlab was used to convert computed the modes to their numerical equivalent as well as the calculation of the complex of the modes with each other ultimately converting them in the frequency domain using Fast Fourier Transform as well as its inverse, iFFT.

All these tools collaborated in their own capability to collect data which was used in this study. Iterative mode computation using Beamprop was the source of the modes that were chosen as input as well as target modes in the experiment. Randomization was also factored to remove a figment of doubt as to the effectiveness of the computed modes that were chosen as well as the source and target modes subsequently produced and investigated.

Mode division multiplexing as an emerging technology has managed to scale [28] the capacity of a single wavelength carrier by increasing the number of modes in a multimode waveguide, and has made it cost-effective in terms of high bandwidth density in on-chip communications. Advanced modulation schemes with high spectral efficiency in MDM networks can further improve [29-31]the data rates of optical links. Because mode division multiplexing uses multimode fiber's spatial modes as data channels to transmit independent data streams, and owing to the fact that many modes are excited in one fiber [32], it is imperative to selectively excite the modes in order to optimize the transmission of data.

Arrayed Waveguide Gratings (AWG)[33][34], Spatial light modulators (SLM) [35], Spiral phase plates [8][9], Fiber Gratings [11][7] where a periodic manipulation [13] of the index of refraction in the fiber core acts like a selective mirror and forms a fibe r Bragg grating [12], are all selective mode excitation techniques which have been effected in wavelength division multiplexing schemes. This paper uses solid core PCF solely because it is a better mode selector to be used with multimode fiber as they have more or less the same structure, implicating that their core diameters can be matched andtherefore, they can be spliced together. This in essence will reduce costs, as well as complexity that is posed by other mode selection techniques in terms of combining the technology with multimode fiber during the transmission process of the modes.

It is essential to note that previous literature reveals that PCF has been successfully used as a mode converter for OAM modes [36] in order to increase bandwidth capacity over free space communication. Being able to manipulate the refractive index enables more efficient mode conversion[37]. PCF in the same light has also been implemented using a set of different modes which are LP modes as stated in [38]. TE0/TE1 mode conversion has also been made possible in [39] using Bragg grating. Mode conversion based on plasmonic metasurfacesin [40]sees the incident TE fundamental waveguide mode converted into the TM00, TM10 or TE10 mode, depending on the design parameters of the waveguide. Mode selection is an important characteristic that is harnessed during mode division multiplexing because what is of high priority is to select the modes with the highest power, meaning that these modes will be able to transmit more data, efficiently and effectively. Selective mode excitation has conquered MDM, [41][42]and PCF also facilitate zero dispersion [43, 44]and when connected to MMF it reverses this anomaly. Mode conversion is applied in many schemes to mention a few optical cryptography, switching, and multiplexing. Fig. 3 represents the schematic representation of how the proposed one source to four target modes coverts the modes in the system.

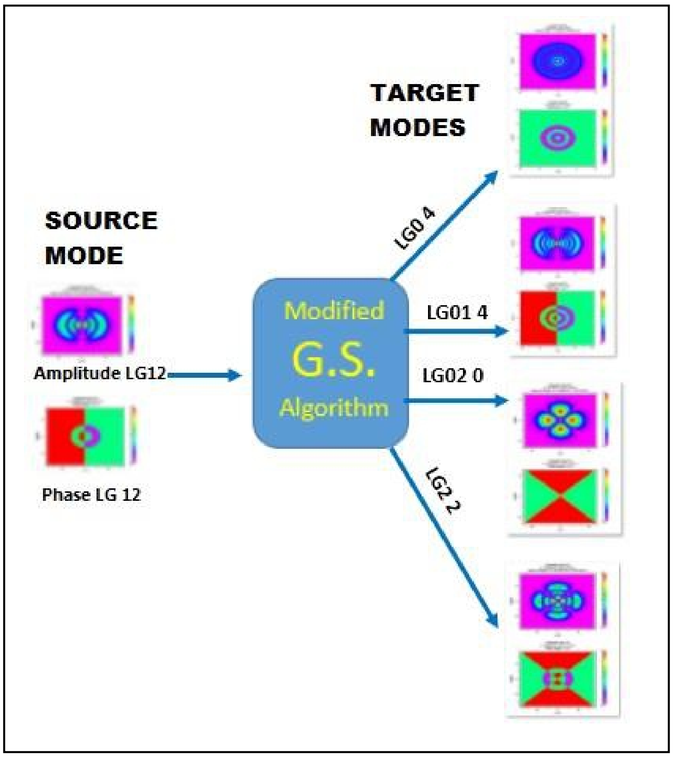


Fig. 3 Schematic representation of one source to four target modes conversion with the Gerchberg-Saxton Algorithm.

In the proposed mode conversion scheme Fig. 4, based on the Gerchberg-Saxton algorithm, one source is assumed as the sender, sending data to four receivers or targets. The amplitude constitutes the part of the mode which is known and will derive the phase on the receiver side. In order to retrieve the phase, the Gerchberg-Saxton algorithm will then be used by the receiver to convert the received binary phase to the continuous amplitude of the complex image. In other words, the Gerchberg-Saxton algorithm will be for the derivation of the phase at the receiver or target.

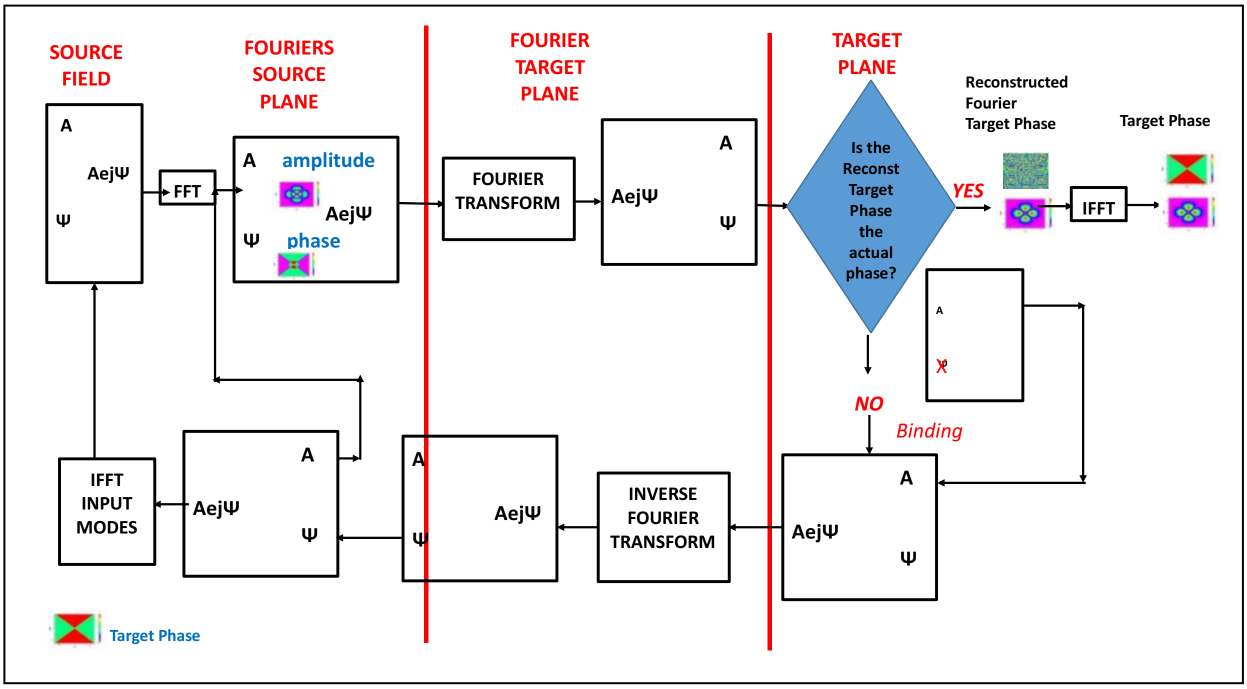


Fig. 4 Flow Chart of the conversion process using the Gerchberg-Saxton Algorithm.

IV. Findings and Results

Traditionally the GS algorithm is very widely used in varying disciplines of modern sciences and technologies where phase retrieval is required. This legendary algorithm iteratively calculates the phase from a known amplitude distribution using numerical simulation techniques. The

Fourier transform propagating function is used, in this paper to retrieve the phase with the knowledge of the amplitude at the respective optical planes. Knowing the phase distribution of the target, is sufficient, for comparison purposes since the phase distribution on the other planes can be obtained by performing a Fourier transform on the plane whose phase is known. The target phase and the reconstructed target phase as well as the target Fourier phase and its reconstructed target Fourier phase are then tallied by calculating their mean square error (MSE). The mean square error is calculated as follows;

$$MSE = \frac{\sum_{M,N}[\,(I_1 m,n)\ I_2(m,n)]^2}{M*N}$$

[1]

Where I_1 and I_2 represent the input images and M and N represent the number of rows and columns in the input images, respectively. Fig. 5 illustrates the similarity and accuracy in the way the GS algorithm reconstructs the target phase as well as the target Fourier phase.

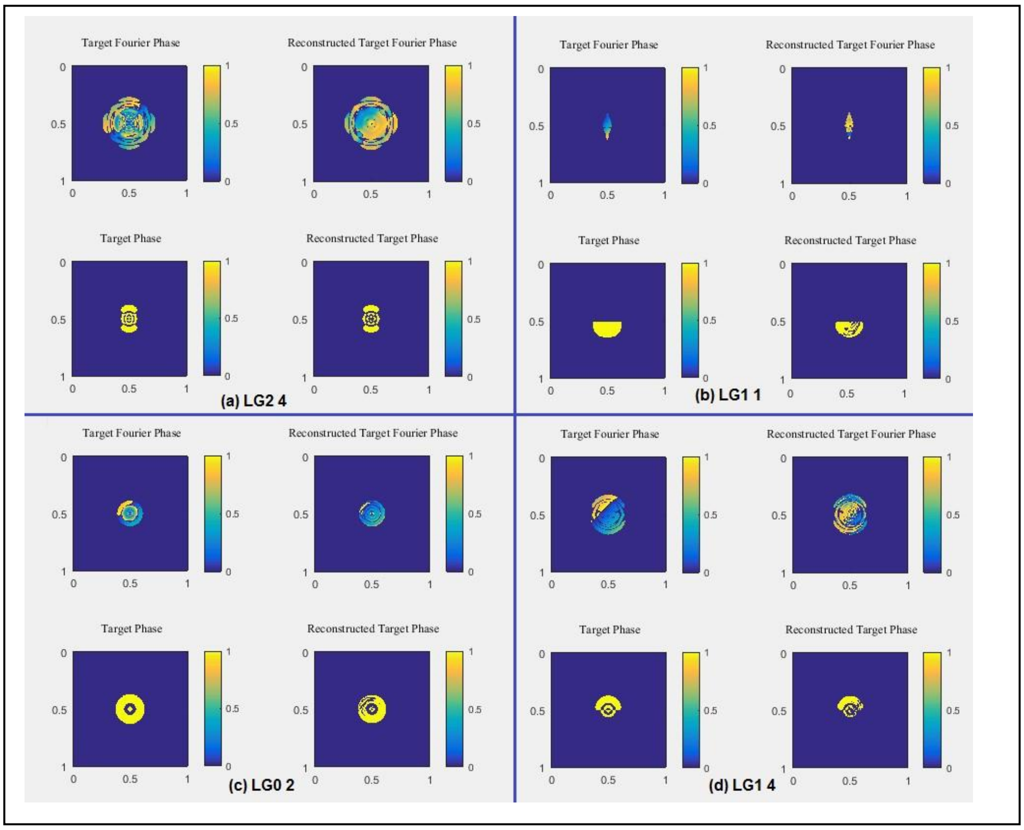


Fig. 5 Accuracy of reconstruction of the Target Fourier Phase and Target phase using the Gerchberg-Saxton Algorithm.

In this paper phase reconstruction from the Fourier magnitudes is achieved through the Gerchberg Saxton iterative algorithm which was developed for phase retrieval, exploiting the magnitude of an image and the Fourier magnitudes as constraints whilst reconstructing the phase from a known amplitude distribution at the source plane. Other researchers have in time employed the other transforms in phase retrieval using different schemes and transforms. Image encryption by amplitude modulation as was employed in [45] for phase retrieval and no iterative algorithm was used. Encryption and decryption in[46]used the phase-truncated Fourier transform (PTFT) for phase retrieval in the proposed cryptosystem. Quantum key distribution in[47][48] also played a part in image phase retrieval as did the amplitude–phase retrieval Yang–Gu algorithm in [49] and the Fast Walsh Hadamard Transform (FWHT) in [50]. As such this paper attempts the mode conversion technique using the Fourier Transform based on the Gerchberg Saxton algorithm to show a different perspective in terms of mode conversion.

The reconstruction process involved making sure that the mode occupancy confined the images within 81% of the padded image of the modes. This contributed to a minimal mean square error and also improved the convergence of the GS algorithm during the mode conversion from source to target modes. Fig. 7 illustrates the Fourier and Inverse Fourier occupancy of the modes.

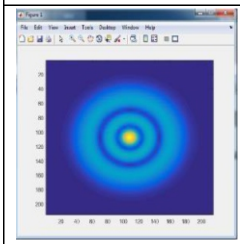
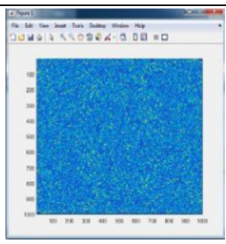
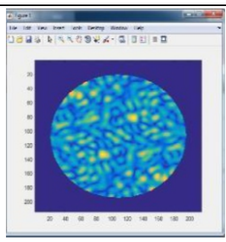
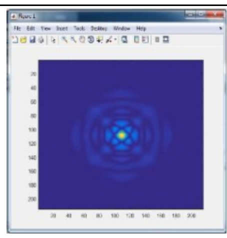
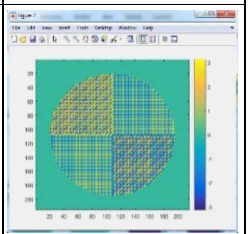
ORIGINAL MODE	**FFT PADDED**	**FFT CROPPED**	**IFFT CROPPED (abs)**	**CROPPED PHASE**
				

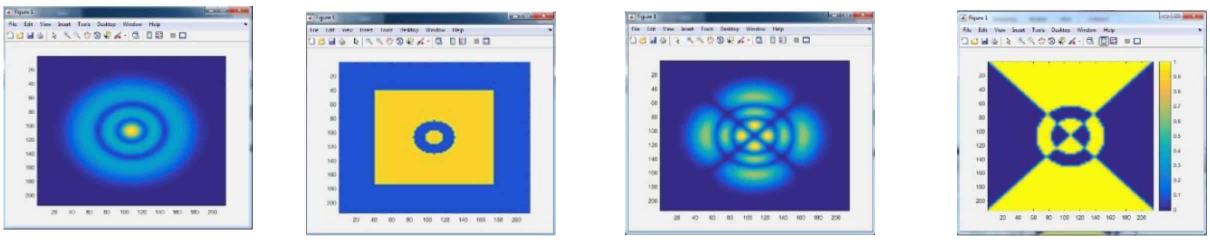
Fig. 7 Mode occupancy in the Fourier domain and Inverse Fourier Transform in the GS algorithm

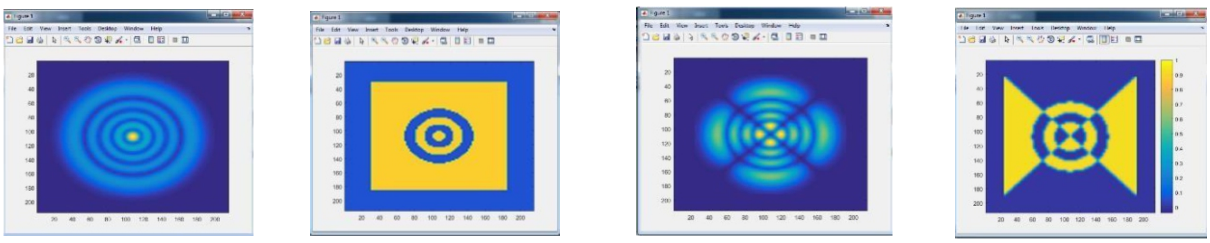
A total of 12 modes Fig.8 and Fig.9, were reconstructed with the aid of the Gerchberg Saxton algorithm. Target Fourier Phase and its reconstructed Target Fourier Phase as well as the Target Phase and the reconstructed target Phase of each mode. The PCF waveguide that was used to compute the modes was designed in RsoftBeamprop[51] then the conversion of one source mode to the target modes was coded in Matlab[52] and the results show that the Gerchberg Saxton Algorithm successfully reconstructed the target Fourier Phase in the Fourier domain as well as the Target phase iteratively. The image processing technique required pre-processing to make sure that the resolution of the images was high as well as the mode occupancy was required to be identical as that of the source mode.

V. Discussion of Results

The Gerchberg Saxton algorithm was used in this paper in order to reconstruct one source mode into four target modes through an iterative modal conversion mechanism via the Fourier domain. Mode conversion is a sensitive procedure which requires the input modes to be pre-processed in order to match the resolution, the mode occupancy as well as the Fourier and inverse Fourier transforms. This will facilitate faster convergence in the iterative algorithm as well as reducing the mean square error between the image of the source mode against the image of the target mode. Fig. 6 illustrates some of the modes that were inserted into the GS algorithm with their occupancy being 81% percent confined within the zero padded portion of the mode which had the images showing in full.

Source amp LG02 Source Phase LG02 Target amp LG22 Target phase LG22





Source amp LG04 Source Phase LG04 Target amp LG23 Target phase LG23

Source amp LG12 Source Phase LG12 Target amp LG24 Target phase LG24

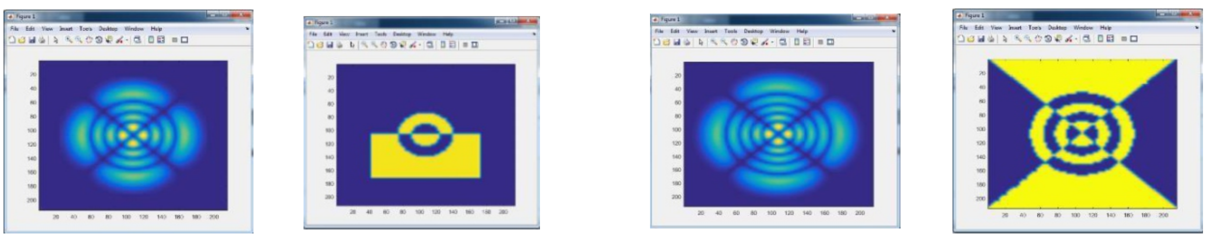


Fig. 6 Mode occupancy of a select source and target modes as inputs into the GS algorithm

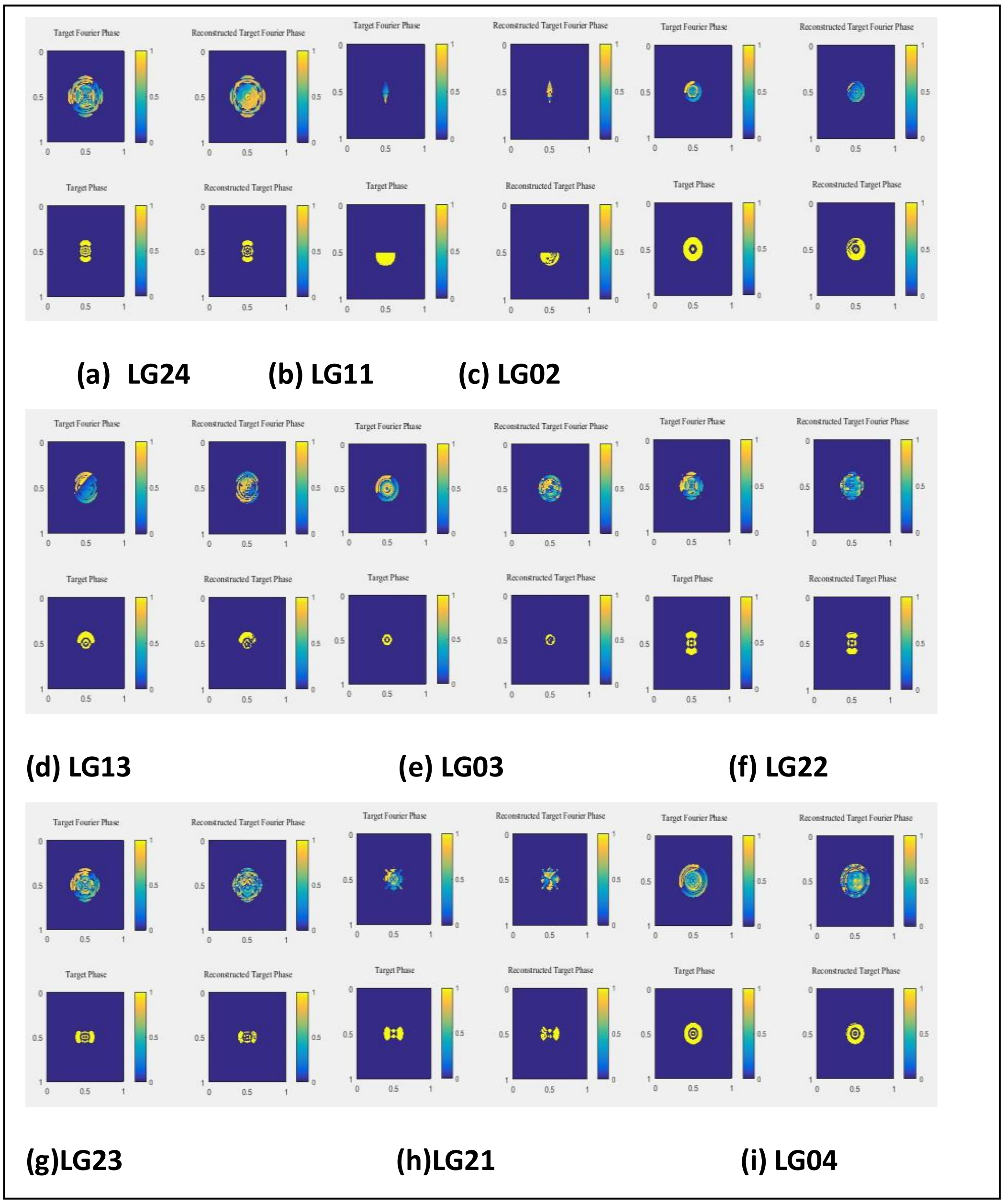


Fig. 8 Reconstruction of the Target Fourier Phase and Target phase of modes LG24, LG11, LG02, LG13, LG03, LG22, 13 Lg23, LG21 and LG04 using the Gerchberg -Saxton Algorithm.

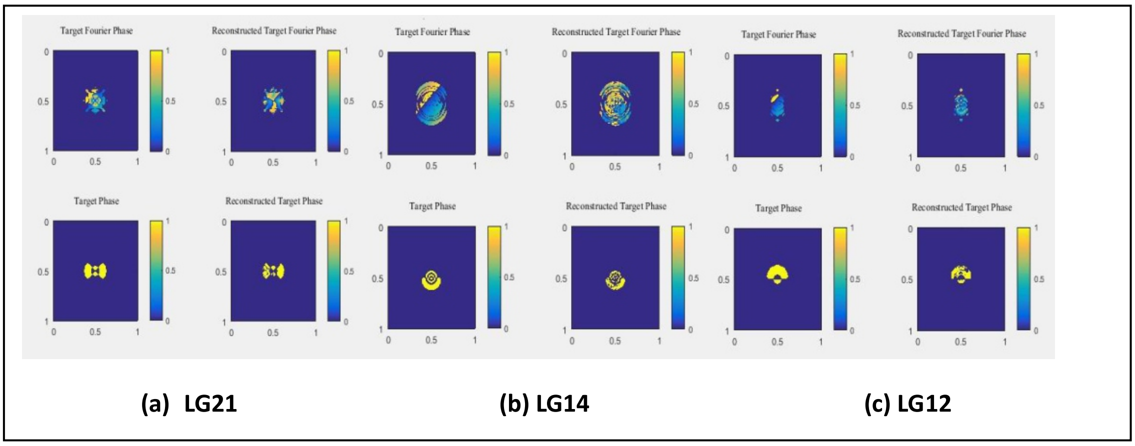


Fig. 9 Reconstruction of the Target Fourier Phase and Target phase of modes LG21, LG14, and LG12using the Gerchberg-Saxton Algorithm.

VI. Conclusions and Recommendations

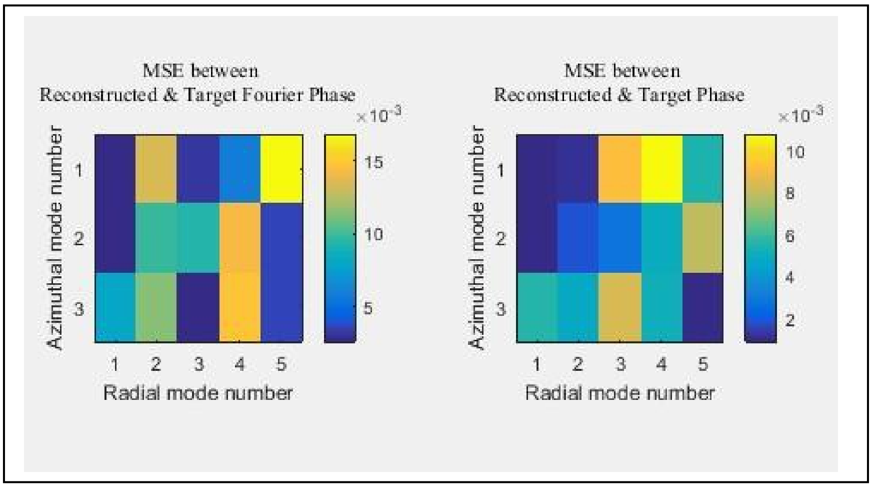


Fig. 10 Mean Square Error between the Reconstructed and Target Fourier Phase as well as the Reconstructed and Target after effecting mode conversion using the Gerchberg-Saxton Algorithm

The mean square error, Fig.10, shows results of between $5x10^{-3}$ and $15x10^{-3}$ for the Target Fourier Phase and Reconstructed Target Fourier Phase, then the mean square error between the Target Phase and Reconstructed Target Phase lies between $2x10^{-3}$ and $10x10^{-3}$. This shows the accuracy and very good performance in terms in terms of image reconstruction capability of the GS algorithm in mode conversion. The recommendations therefore, are to explore optical cryptography using the Gerchberg Saxton algorithm in order to do a pilot for securing optical data for the future. Incubation and further research could be undertaken in order to diversify the experiment from being a simulation to the physical laboratory. Additionally, this futuristic study will be in fulfillment of Goal 9 of the SDGs which aims to “Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation - Industry, Innovation and Infrastructure.

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