Speckled-learned Classification of Partially Coherent Vortex Beams

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Abstract: Speckle-based deep learning approach for the classification of partially coherent vortex beams is presented. Remarkably, this approach achieved 100% classification accuracy. © 2023 The Author(s)

1. Introduction

Laguerre-Gaussian vortex beams, exhibiting quantized Orbital Angular Momentum due to their unique helical phase front are advancing research and enhancing communication bandwidth and information. Traditional techniques for differentiating these OAM modes, which depend on interference and diffraction, are often complicated and require a precise alignment for high recognition accuracy [1]. To overcome that speckle-based deep learning approach to classify the beams were successfully demonstrated [2, 3], however, the classification of partially coherent vortex modes needs to be explored.

Optical coherence is the inherent degree of freedom of light beams and has been utilized as a fundamental resource in optical communication [4, 5]. Partially coherent beams offer distinct advantages over fully coherent beams in free-space optical (FSO) laser communications, particularly due to their increased resilience against atmospheric turbulence. Measurement of spatial coherence [6] of light is the key to utilizing its full potential. Classification of the partially coherent vortex beams is another challenging task for its effective use. Here we are proposing the speckle-based deep learning approach [2] for the classification of partially coherent vortex beams.

2. Generation of partially coherent vortex beams and their speckle patterns

There are many ways to generate the partially coherent vortex such as using Schell Model sources, beam propagation method, coherent mode decomposition methods, etc. [6]. We simulated the partially coherent vortex beams (I_l) of charge l as the incoherent superposition of randomly shifted optical vortex fields [7], $\langle I_l(x,y)\rangle = \frac{1}{N}\sum_{k=0}^{N} E_k^* E_k$, here $E_k = LG_{0l}\big(x-a_j, y-b_j\big)exp(i\varphi_j)$ are the randomly shifted LG_{0l} beams with vortex center (a_j, b_j) and having the constant uniform random phase φ_j. Fig.1 shows the adopted scheme to generate the partially coherent beams and Fig 2 a) shows the simulated partially coherent beams of charge $l = 1 - 4$ with $N = 100$.

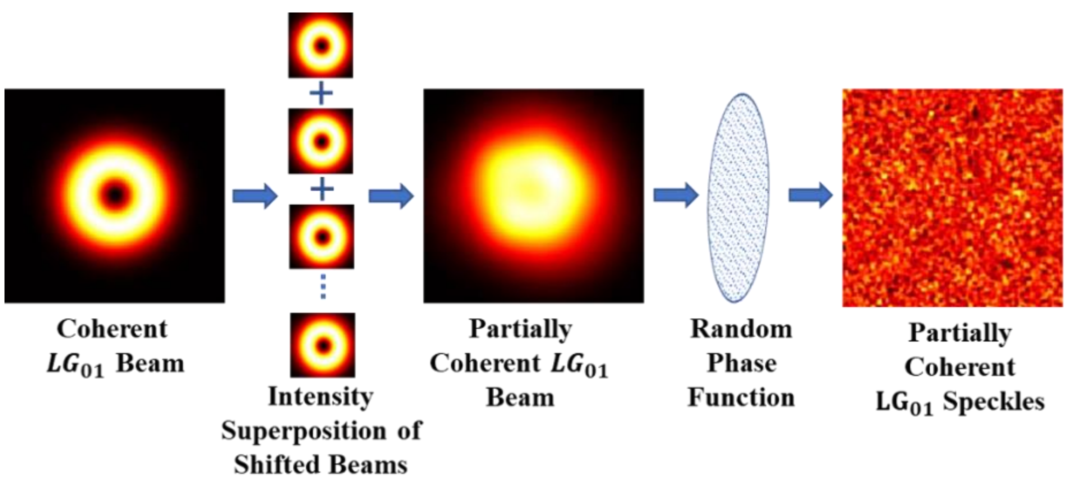

Fig. 1. Scheme for the generation of Partially Coherent Vortex Beams and their corresponding Speckle patterns.

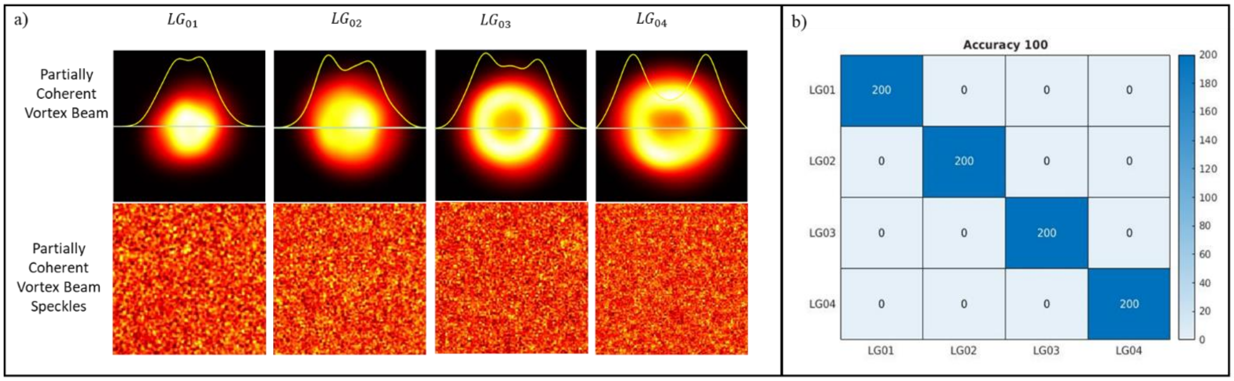

Fig.2 a) Simulated partially coherent vortex beams with vortex charge $l = 1-4$ and their corresponding speckle patterns. b) Confusion matrix of classified partially coherent vortex beams.

3. Speckled-learned Classification of Partially Coherent Vortex Beams

To classify the partially coherent beams, a speckle-based deep learning approach is adopted. In this approach, a small region of the speckle patterns is sufficient for the classification and it is alignment-free and more robust against noise [2]. The speckle patterns of the partially coherent vortex beams (I_l^{sp}) are simulated using the equation, $\langle I_l^{sp}(x,y)\rangle = \frac{1}{N}\sum_{k=0}^{N} E_k^* E_k$ $E_k = \mathcal{F}\{LG_{0l}(x-a_j, y-b_j)e^{i\varphi_j}e^{i\phi_R}\}$, $(\phi_R(x,y))$ is spatially varying random phase and $\mathcal{F}$ is the Fourier transform. The deep learning analysis of the partially coherent vortex beam's speckle patterns requires a huge data, therefore, a dataset of the speckle patterns of the partially coherent vortex beams with vortex charge $l = 0-4$ is created. The dataset constitutes a total of 4000 speckle images, 1000 speckle images for each partially coherent vortex beam. The deep learning model, a pre-trained network, AlexNet is modified [2] to perform the classification. The dataset is partitioned in an 80:20 ratio, using the larger portion for model training and the remaining portion for model evaluation. The analyzed confusion matrix with 100% classification accuracy of partially coherent vortex beams is shown in Fig. 2 b).

4. Conclusion and Analysis

We have presented a novel approach for the classification of partially coherent optical vortex beams by employing a speckle-based deep learning approach. Our methodology is a single-shot intensity measurement to classify partially coherent vortex beams. Using the adopted approach we can accurately classify all four beams with 100% classification accuracy which signifies that our method is an efficient and highly accurate approach for the classification of partial coherent optical vortex beams. In conclusion, we anticipate our method to significantly contribute to the coherent and partially coherent optical beam classification and inspire further interdisciplinary work at the junction of optics and machine learning.

5. Acknowledgment: SERB India (SRG/2021/001375).

6. References

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Abstract: Speckle-based deep learning approach for the classification of partially coherent vortex beams is presented. Remarkably, this approach achieved 100% classification accuracy for the simulation results.

Partially Coherent Vortex Field Equation

Coherent Vortex Beam

$$LG_{l,m}(r) = A_{l,m}\left[\frac{W_0}{W(z)}\right]\left(\frac{\rho}{W(z)}\right)^{l}\mathcal{L}_m^{l}\left(\frac{2\rho^2}{W^2(z)}\right)exp\left(-\frac{\rho^2}{W^2(z)}\right)\times exp\left[-ikz-ik\frac{\rho^2}{2R(z)}\mp il\phi+i(l+2m+1)\zeta(z)\right]$$

Intensity of Partially Coherent Vortex Beam

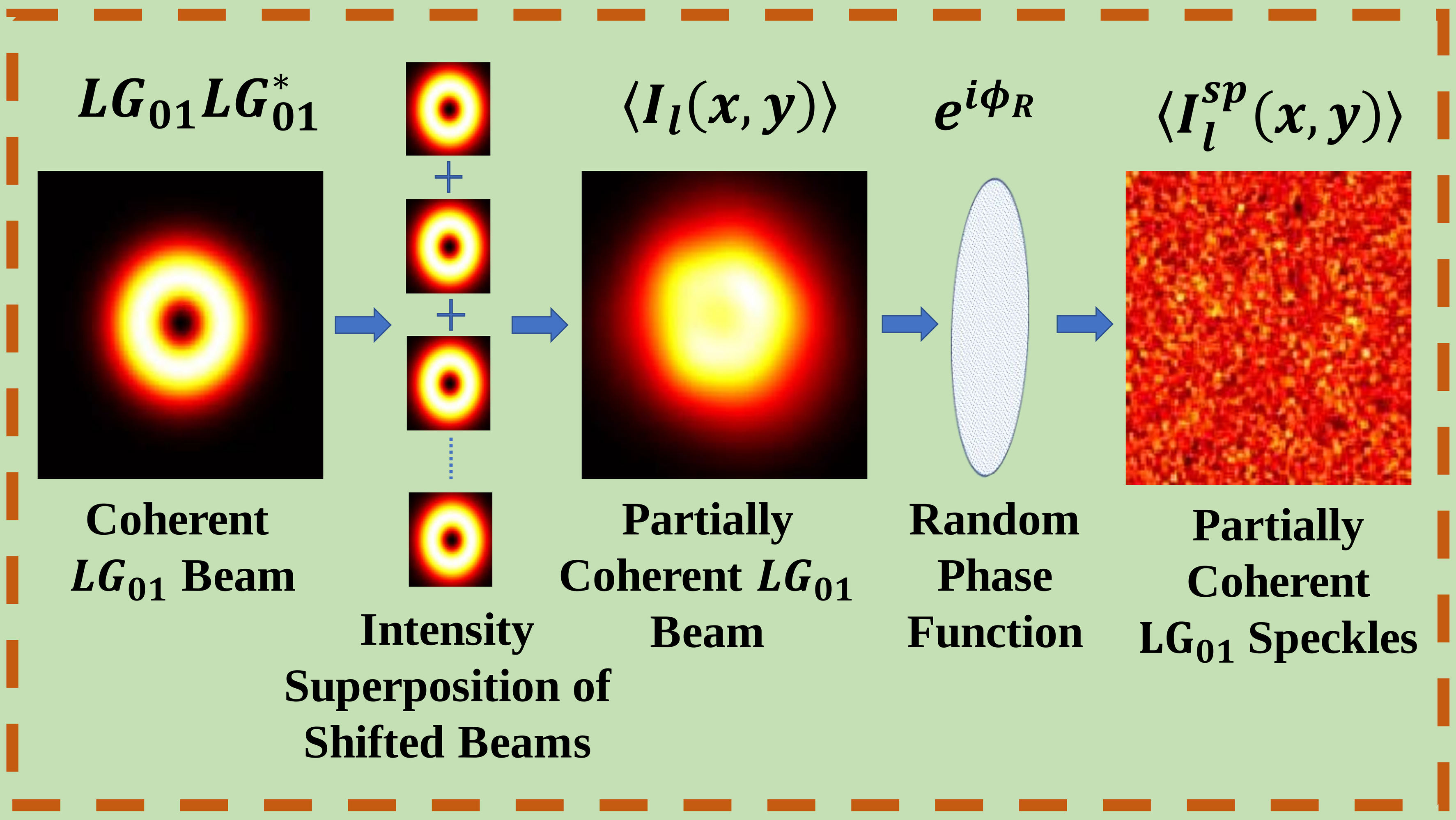
$$\langle I_l(x,y)\rangle = \frac{1}{N}\sum_{k=0}^{N} E_k^{*}E_k\,,\quad \text{where } E_k = LG_{0l}(x-a_j, y-b_j)exp(i\varphi_j)$$

Intensity Speckle of Partially Coherent Vortex Beam

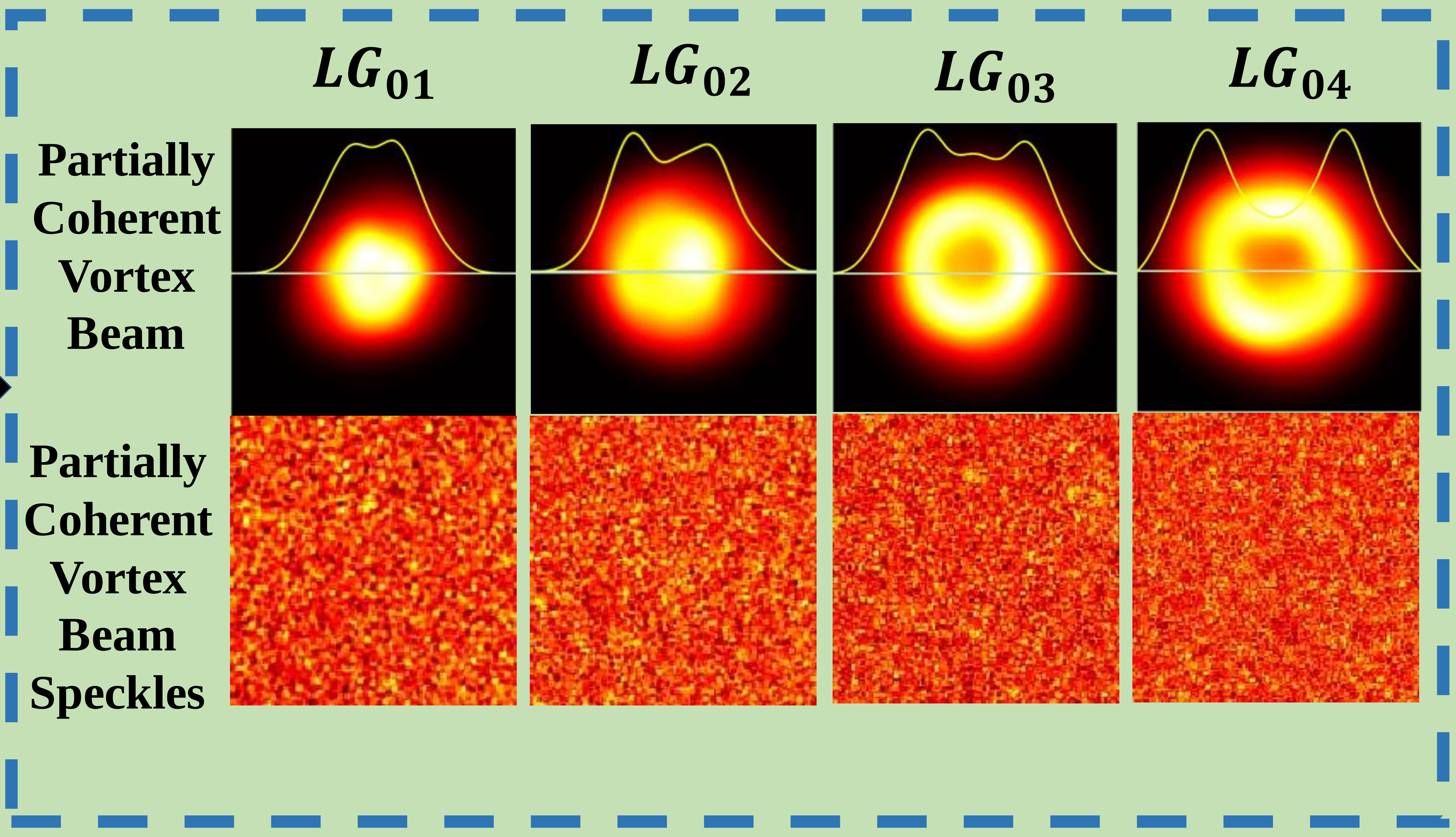
$$\langle I_l^{sp}(x,y)\rangle = \frac{1}{N}\sum_{k=0}^{N} E_{sp}^{*}E_{sp}\quad \text{where } E_{sp} = \mathcal{F}\{LG_{0l}(x-a_j, y-b_j)e^{i\varphi_j}e^{i\phi_R})\}$$

(a_j, b_j) are shifted vortex centers, φ_j is constant uniform phase, $(\phi_R(x,y))$ is spatially varying random phase, $\mathcal{F}$ is the Fourier transform and parameters $l = 1 - 4$ & $N = 100$

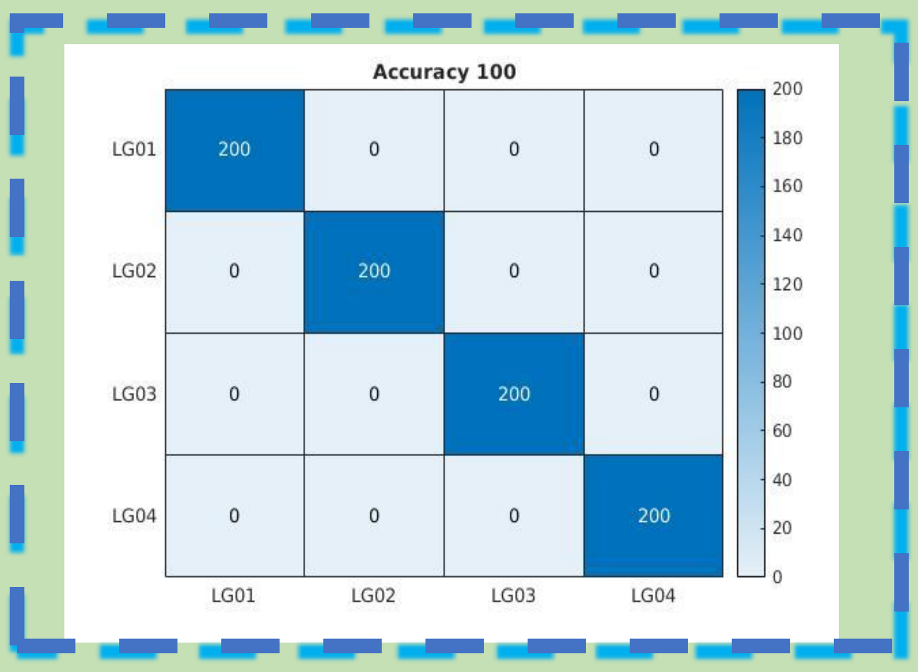
(a) Generation of Partially Coherent Vortex Field



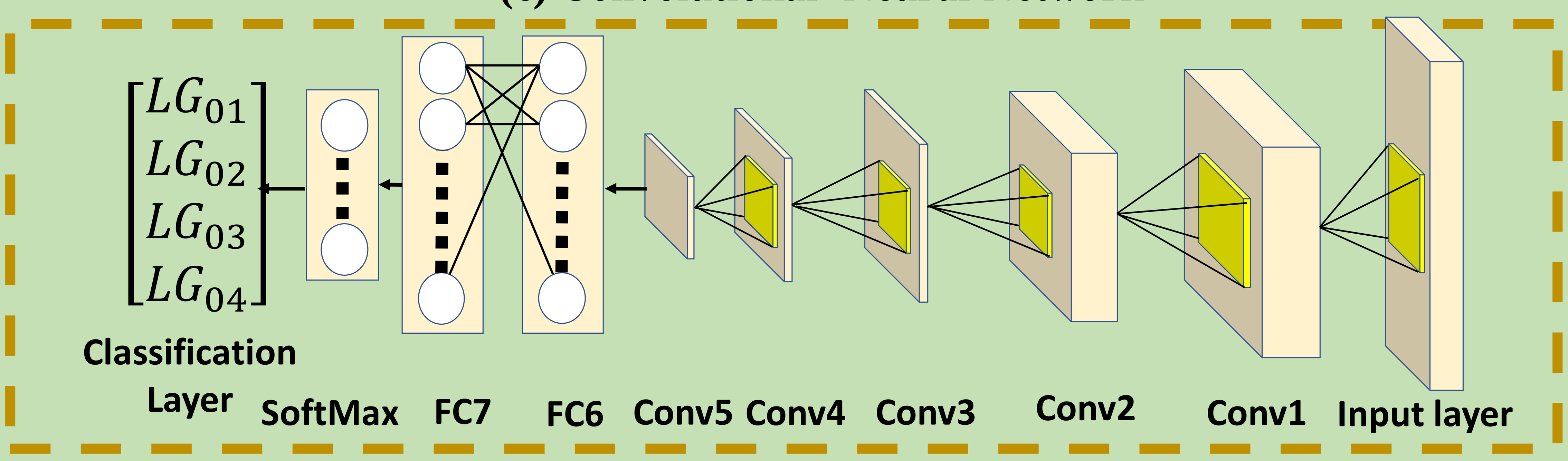
(b) Partially Coherent Field and Corresponding Speckles



(d) Confusion Matrix



(c) Convolutional Neural Network



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